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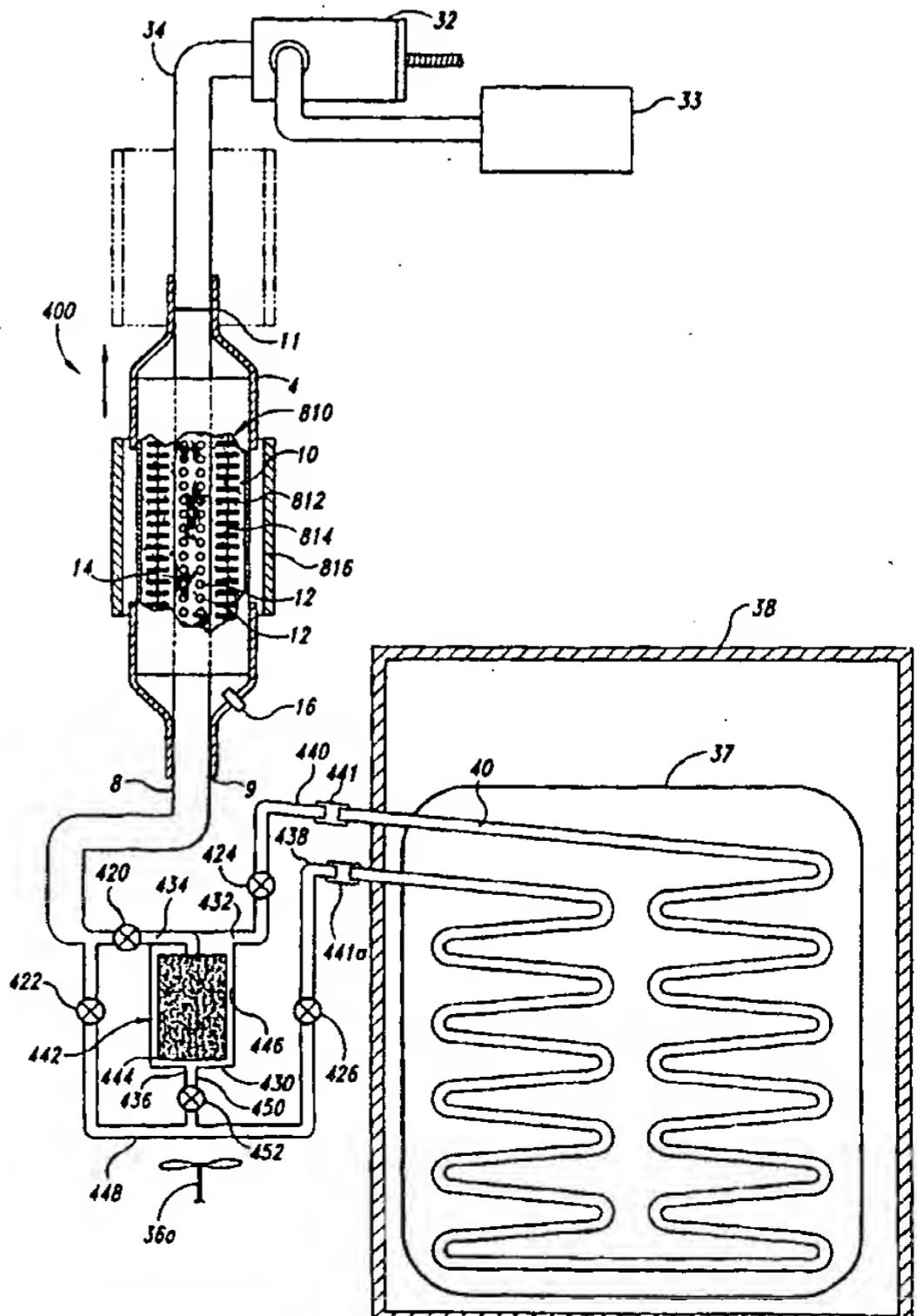
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(54) Title: ADSORBENT REFRIGERATOR WITH SEPARATOR

(57) Abstract

A heat transfer apparatus (2) that uses an adsorbent material (10) to generate a cooling effect. The heat transfer apparatus (2) includes a first vessel (4) containing adsorbent material (10) and a second vessel (6) interconnected to the first (4). A working substance is contained within the two interconnected vessels (4, 6). The working substance is drawn as a vapor out of the second vessel (6) and toward the first vessel (4) to cool the second vessel (6). A separator device (430) separates at least part of the vapor passing from the second vessel (6) toward the first vessel (4) to delay the point at which the adsorbent material (10) in the first vessel (4) becomes saturated with vapor. The adsorbent material (10) may include a carbon fiber (613, 910) that desorbs the working substance when electrical current is passed therethrough. The carbon fiber (613) may also be positioned within a container (600) to displace fluid in the container (600) when the carbon fiber is desorbed.



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ADSORBENT REFRIGERATOR WITH SEPARATOR

TECHNICAL FIELD

The present invention is generally directed to a heat transfer apparatus that uses an adsorbent material to generate a cooling effect.

5 BACKGROUND OF THE INVENTION

Adsorption has previously been employed to generate a refrigeration effect. Adsorption is a process which utilizes the natural affinity certain adsorbent materials have for adsorbates. A typical refrigeration cycle employing adsorption includes two phases. During one phase, the dried or charged adsorbent material is exposed to a liquid adsorbate. The affinity the adsorbent has for the adsorbate causes the adsorbate to enter a vapor state as it is attracted to the adsorbent. The conversion of the adsorbate from a liquid state to a vapor state is an endothermic reaction which extracts heat from the environment surrounding the liquid, and therefore cools the environment and heats the adsorbent. During the second phase, additional heat is supplied to the adsorbent to expel or desorb the adsorbed vapor, thereby recharging the adsorbent. The desorbed vapor is condensed and cooled, and the two phase cycle is repeated.

Zeolite (also called a molecular sieve), is a general term for crystalline metal-alumosilicate adsorbents which are similar to sand in chemical composition. More than 40 natural and 100 synthetic zeolites are presently known. Zeolite has a large internal surface area of up to $100 \text{ m}^2/\text{g}$, and a crystal lattice with strong electrostatic fields. Zeolite retains adsorbates by strong physical forces rather than by chemisorption. This means that when the adsorbed molecule is desorbed by the application of heat or by displacement with another material, it leaves the crystal in the same chemical state as when it entered. The very strong adsorptive forces in zeolite are due primarily to the cations which are exposed in the crystal lattice. These cations act as sites of strong localized positive charge which electrostatically attract the negative end of polar molecules. The greater the dipole moment of the molecule, the more

strongly it will be attracted and adsorbed. Polar molecules are generally those which contain O, S, Cl, or N atoms and are asymmetrical. Water is one such molecule. Under the influence of the localized, strong positive charge on the cations, molecules can have dipoles induced in them. The polarized molecules are then adsorbed strongly due to the electrostatic attraction of the cations. The more unsaturated the molecule, the more polarizable it is and the more strongly it is adsorbed.

Desorption from zeolite powders shows no hysteresis. The adsorption and desorption are completely reversible. With pelleted zeolite material, however, some further adsorption may occur at pressures near the saturation vapor pressure through condensation of liquid in the pellet voids external to the zeolite crystals. Hysteresis may occur on desorbing this macro-port adsorbate.

In a typical installation, an adsorbent vessel and a condensing vessel are interconnected. The adsorbent vessel contains an adsorbent such as zeolite and the condensing vessel contains a working fluid, such as the water brine mixture disclosed in U.S. Patent No. 4,584,842. Assuming the adsorbent is in an uncharged state, the adsorbent vessel is heated to vaporize any working fluid contained therein and drive the fluid from the adsorbent vessel to the condensing vessel where it condenses. Both vessels are then cooled. As the adsorbent vessel cools, it begins to adsorb vapor from the working fluid in the condensing vessel. As the working fluid enters the vapor state, it adsorbs the heat of vaporization from its surroundings, which cools the condensing vessel and the working fluid remaining in the condensing vessel. When the adsorbent is saturated with working fluid vapor, the cycle is complete. The adsorbent vessel is then reheated, causing the vapor to return to the condenser and condense, repeating the previous cycle.

One drawback of the devices described above is that the working fluid, which is typically water, requires the addition of salt to form a brine mixture. Without the brine, the water will completely freeze and expand, breaking the condensing vessel and associated hardware. For example, the condensing vessel ideally includes thin, finned heat exchanger tubes to maximize the cooling rate in the condensing vessel. Such tubes are particularly prone to failure when subjected to freezing water. In

addition, the brine remaining in the condensate vessel tends to harden when the working fluid is adsorbed, reducing the efficiency of heat transfer from the condensate vessel.

A further drawback of existing adsorbent refrigerators is that the capacity of the adsorbent is not matched to the volume of working substance. If the adsorbent capacity is too low, the adsorbent becomes saturated while there is still working substance in either a fluid or a solid state. This is inefficient because the adsorbent must be recharged more often than it would if it were sized to completely adsorb all the working fluid. If the adsorbent capacity is too high, the adsorbent vessel is larger than necessary and therefore inefficient to heat.

Accordingly, there is a need in the field for an adsorption apparatus which matches the quantity of the working substance to the capacity of the adsorbent and which can continue to adsorb the working substance whether the working substance is in a fluid state or a solid state without causing damage to the apparatus. The present invention fulfills these needs and provides further related advantages.

15 SUMMARY OF THE INVENTION

In brief, this invention is directed to a heat transfer apparatus that uses an adsorbent material to generate a cooling effect. The invention provides an improvement over the prior art because it is capable of adsorbing a working substance from the solid phase as well as the liquid phase, thereby eliminating the need for brine or other additives which reduce the freezing point of the working substance. The invention provides a further improvement over the prior art because the amount of adsorbent material is balanced to adsorb substantially all the working substance, thereby maximizing the cooling effect of the working substance contained within the heat transfer apparatus.

In one embodiment of the present invention, the apparatus includes a first vessel containing adsorbent material and a second vessel connected to the first with a conduit. The conduit provides a fluid passage between the vessels and the vessels together with the conduit form a sealed volume capable of maintaining a pressure below atmospheric pressure. The sealed volume contains a quantity of working substance

which is selected to be substantially completely adsorbed by the adsorbent material. As the working substance is adsorbed, it cools the second vessel. Once the working substance has been completely adsorbed, the first vessel is heated to desorb the working substance back to the second vessel.

5 In a further aspect of the invention, a portion of the working substance located in the second vessel is in the solid state. The solid state working substance is completely adsorbed by sublimation into the adsorbent material contained in the first vessel.

In a further embodiment of the invention, the second vessel is housed
10 within an insulated refrigeration chamber. During adsorption, the second vessel cools the refrigerated chamber in a manner suitable for storage of foodstuffs or other substances which require refrigeration.

In still a further embodiment of the present invention, a second vessel is adapted to be used with working substances which expand upon freezing. The second
15 vessel contains a compressible material which compresses as the working substance changes from a liquid state to a solid state. The amount of compressible material contained within the second vessel and the amount of working substance contained therein are selected such that when the working substance freezes, the force exerted by the working substance and the compressed compressible material on the second vessel
20 is less than the burst pressure limit of the second vessel.

In yet a further embodiment of the invention, the first vessel is used to heat the hot reservoir of a Stirling engine and the second vessel is used to cool the cold reservoir of the engine. The first and second vessels thereby increase the temperature differential of the reservoirs between which the Stirling engine operates and increase the
25 efficiency of the engine.

In another embodiment of the invention, the conduit between the first and second vessels contains a turbine. The turbine is coupled to a power transmission device outside the conduit such that when vapor is passed from the second conduit to the first conduit by adsorption, the vapor rotates a rotor in the turbine, generating power
30 which is transmitted to the power transmission device.

In a further embodiment of the present invention, the heat transfer apparatus includes a thermal voltaic device having a hot side and a cold side. The apparatus is positioned to increase the temperature of the hot side with the adsorbent vessel and decrease the temperature of the cold side with the condensing vessel, thereby increasing the voltage output of the thermal voltaic device.

The present invention also provides a method for transferring heat and a working substance between a first vessel containing an adsorbent material and a second vessel connected to the first vessel with a conduit. The method comprises allowing a liquid portion of the working substance to vaporize by adsorption and transfer from the second vessel to the first vessel, thereby causing a remaining portion of the liquid working substance in the second vessel to freeze, and continuing to adsorb the frozen portion of the working substance by sublimation until the working substance has been completely adsorbed.

In a further embodiment of the present invention, a separator device is connected in fluid communication with the conduit between the first and second vessels. The separator removes a part of the working substance which passes from the second vessel to the first during adsorption. The part of the working substance removed by the separator may be returned to the second vessel for another cycle without requiring the first vessel to be heated. The separator device therefore delays the point at which the first vessel is heated to desorb the working substance.

In yet a further embodiment of the invention, the first vessel and separator device are coupled to a hydrogen-oxygen fuel cell. The adsorbent material in the first vessel draws water from the fuel cell, thereby cooling the cell and improving the fuel cell efficiency. The separator device may be used to remove a portion of the water passing out of the fuel cell to delay the point at which the first vessel must be desorbed.

In a further embodiment of the invention, the first vessel includes a heat transfer conduit in thermal contact with the adsorbent material. In one such embodiment, the heat transfer conduit includes an electrical heating element to heat the adsorbent material in the first vessel during desorption. The heat transfer conduit is

coupled to a source of cooling air to cool both the conduit and the first vessel after desorption. In another such embodiment, the electrical heating element is removed and hot and cold air are alternately passed through the heat transfer conduit to desorb the working substance and cool the adsorbent material. In yet another such embodiment, 5 the first vessel includes heat transfer tubes in thermal contact with the adsorbent material. The heat transfer tubes conduct hot fluid to desorb working substance from the first vessel, supplementing the heat provided by the heat transfer conduit, and conduct cold fluid to cool the first vessel after desorption.

In yet a further embodiment of the invention, the second vessel includes 10 a first container having substantially rigid walls and a second container positioned within the first and having flexible walls. The flexible walls are expandable to force the working substance positioned between the first and second containers toward the rigid walls of the first container to increase the heat transfer between the first container and its environment.

15 In still a further embodiment of the invention, the second vessel includes a substantially rigid wall connected to a flexible wall to define an interior volume containing the working substance. The flexible wall is displaceable when the working substance freezes and expands to prevent the second vessel from bursting.

In yet another embodiment of the invention, the adsorbent material may 20 include a carbon fiber material that desorbs water when electrical current is passed therethrough and that adsorbs water when the current is removed. The carbon fiber material may be used to create a cooling effect, or may be used to displace liquids or gases to form valves, pumps, or other displacement devices.

These and other aspects of this invention will become evident upon 25 reference to the following detailed description and attached drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

Figure 1 is a partially cut away side view of an embodiment of the present invention with an adsorbent vessel coupled to a condensate vessel.

Figure 2 is a cross-sectional view of an embodiment of the invention in which the condensate vessel includes heat exchanger tubing and is housed in a refrigerated box.

Figure 3 is a side view detail of the heat exchanger tubing of Figure 2
5 including a compressible material insert and fins.

Figure 4 is a cross-sectional view taken substantially along line 4-4 of
Figure 3.

Figure 5 is a detail of the compressible material insert of Figure 3.

Figure 6 is an embodiment of the present invention in which two
10 adsorbent vessels are connected to a single condensate vessel.

Figure 7 is an embodiment of the present invention in which two adsorbent vessels are each connected to separate heat exchangers to provide for continuous cooling of the refrigerated box.

Figure 8 is a schematic view of an alternate embodiment of the present
15 invention in which two adsorbent vessels are used in conjunction with the condensate vessel to drive a turbine.

Figure 9 is a schematic of an alternate embodiment of the present invention in which the adsorbent vessel and condensate vessel are integrated into a basic Stirling engine cycle.

20 Figure 10 is an embodiment of the present invention in which two adsorbent vessels are connected to a single condensate vessel and includes accumulators for pre-condensing a working substance.

Figure 11 is an embodiment of the present invention which includes both gas-fired and electric heat sources.

25 Figure 12 is an embodiment of the invention which includes an internal heat source, retaining machined adsorbent material, and an external annular heating or cooling device.

Figure 13 is a cross-sectional view of the embodiment of Figure 12 taken substantially along line 13-13.

Figure 14 is an embodiment of the invention which includes a hollow internal heat transfer source and an external annular heat transfer source, both heat transfer sources being suitable for heating or cooling the adsorbent material.

Figure 15 is a cross-sectional view of the embodiment of Figure 14 taken substantially along line 15-15.

Figure 16 is a partially cut-away side view of an embodiment of the present invention having a separator device positioned in a conduit connecting an adsorbent vessel and a heat exchanger.

Figure 17 is a partially cut-away side view of an embodiment of the present invention with a plurality of heat exchangers coupled to a separator device and a single adsorbent vessel.

Figure 18 is a partially cut-away side view of an embodiment of the present invention having an electrical heater positioned within a heat transfer conduit of an adsorbent vessel.

Figure 19 is a partially cut-away side view of an alternate embodiment of the heat transfer conduit of Figure 18.

Figure 20 is a partially cut-away side view of an embodiment of the present invention having an adsorbent vessel and separator coupled to a hydrogen-oxygen fuel cell.

Figure 21 is a partially cut-away side view of an embodiment of the present invention with a ferromagnetic material positioned within an adsorbent vessel.

Figure 22 is a cross-sectional view of an alternate embodiment of the heat exchanger tubing of Figure 16 including an expandable inner container.

Figure 23 is an alternate embodiment of the heat exchanger tubing of Figure 21 including an expandable tubing wall.

Figure 24 is an alternate embodiment of the heat exchanger of Figure 16.

Figure 25 is an exploded isometric view of an apparatus having carbon material in accordance with another embodiment of the invention.

Figure 26 is an isometric view of another embodiment of the carbon material shown in Figure 25.

Figure 27 is an isometric view of an apparatus having coated carbon materials in accordance with another embodiment of the invention.

Figure 28 is an isometric view of a ferromagnetic material attached to a solid heat sink in accordance with another embodiment of the invention.

5 Figure 29 is a cross-sectional view of an alternate embodiment of the heat exchanger tubing shown in Figure 22.

Figure 30A is a partially broken side elevation view of a conduit having a bladder valve in accordance with another embodiment of the invention.

10 Figure 30B is a partially broken side elevation view of a conduit having a plurality of bladders in accordance with still another embodiment of the invention.

Figure 30C is a partially broken side elevation view of a conduit having a plurality of adsorbent material pellets in accordance with yet another embodiment of the invention.

15 Figure 31 is an isometric view of part of an array of interconnected adsorbent material portions.

DETAILED DESCRIPTION OF THE INVENTION

As mentioned above, the present invention is directed to an apparatus for using a heat source to generate a refrigerating effect. The apparatus includes an adsorbent material which cyclically adsorbs and desorbs a working substance, causing a transfer of heat. The present invention increases the efficiency of the adsorption cycle by matching the capacity of the adsorbing material to the quantity of working substance. The invention further increases the efficiency of the adsorption cycle by retaining the working substance in a vessel which does not burst when the working substance solidifies, thereby permitting adsorption to continue after the working substance has solidified.

A representative apparatus in accordance with the present invention is shown in the figures for purposes of illustration. As shown in Figure 1, an adsorbent vessel 4 of an apparatus 2 is connected to a condensate vessel 6 with a pipe 8 which passes through an aperture 9 located in the base of the adsorbent vessel. The adsorbent

vessel 4 is packed with an adsorbent material 10 which has a strong affinity for polar working substances. The pipe 8 extends through the adsorbent vessel 4 and is surrounded by the adsorbent material 10. The pipe 8 contains perforations 12 which permit vapor to pass back and forth between the adsorbent material 10 and the pipe. A 5 mesh cloth 14 covers the perforations 12 and prevents adsorbent material 10 from entering the pipe 8 through the perforations. The adsorbent vessel 4 contains a plug 16 for draining of the adsorbent vessel and for access to the vessel for purposes of maintenance.

A heat source 18 is located adjacent to the adsorbent vessel 4 and is 10 positioned to heat the adsorbent vessel and its contents. The heat source 18 may be cycled between an active position in which it generates heat, heating the adsorbent vessel 4 and causing the adsorbent material 10 to release vapors (desorb), and an inactive position in which the adsorbent vessel 4 and its contents are permitted to cool. The heat source may take the form of an electric heater, combustion heater, the sun, or 15 heating may be accomplished by passing magnets over copper tubing, for example, the vessel 4. Other heating methods known in the art may be used as well.

In one embodiment, the pipe 8 contains a vacuum valve 20 and a bellows 22. The vacuum valve 20 is movable between an open position, as shown in solid lines 20 in Figure 1 wherein the condensate vessel 6 may communicate with the adsorbent vessel 4 through the pipe 8, and a closed position indicated in phantom lines in Figure 1 wherein the condensate vessel is sealed from communication with the adsorbent vessel. The condensate vessel 6 contains a viewing window 24 which permits viewing the condensed liquid working substance 26 and solid working substance 28 contained in the condensate vessel. In another embodiment, the vacuum valve 20 and bellows 22 are 25 replaced with a commercial-grade vacuum valve, or other suitable valving device.

The adsorbent vessel 4 contains a second aperture 30 which is connected to a vacuum valve 32 by a pipe 34. The vacuum valve is connectable to a vacuum source 33 for purposes of evacuating the adsorbent vessel 4. An expansion joint 11 is provided between the pipe 34 and the adsorbent vessel 4 to account for thermal 30 expansion of the pipe and adsorbent vessel during desorption. It is desirable to reduce

the pressure in the adsorbent vessel 4 in order to lower the temperature at which the liquid working substance 26 will vaporize and be adsorbed by the adsorbent material 10. However, depending upon the characteristics of the adsorbent material 10 and the working substance, pressures at and above atmospheric pressure are possible as well.

5 The vacuum valve 32 is positionable between an open position which permits communication between the adsorbent vessel 4 and the vacuum source 33, and a closed position in which the adsorbent vessel 4 is sealed from the vacuum source.

Prior to operation of the apparatus 2, the vacuum valve 32 is opened, providing a fluid connection between the adsorbent vessel 4 and the vacuum source 33.

10 The vacuum valve 20 is then opened, providing a fluid connection between the adsorbent vessel 4 and the condensate vessel 6. The pressure in the adsorbent vessel 4 and condensate vessel 6 is reduced. The vacuum valve 32 is then closed and the apparatus 2 is ready for operation. In one embodiment, the pressure within the vessel 4 is reduced to an absolute pressure of 4 mm of mercury (*i.e.*, 4 mm of mercury above 15 total vacuum), however other pressures are possible as well, depending on the type of adsorbent material 10 and working substance contained within the apparatus, as well as the temperature the apparatus is subject to.

In operation, the apparatus 2 cycles between an adsorption phase and a desorption phase. In the desorption phase, the heat source 18 is activated and heats the adsorbent vessel 4 and the adsorbent material 10, causing any liquid working substance contained in the adsorbent material 10 to vaporize. The working substance vapor passes from the adsorbent material 10, through the mesh cloth 14 and perforations 12, into the pipe 8 and then into the condensate vessel 6 where it condenses, forming a pool of liquid working substance 26. In one embodiment, wherein the working substance is water, the adsorbent vessel is heated to a temperature of 250°F to desorb the working substance vapor. Other temperatures are possible as well, depending upon the characteristics of the adsorbent material 10, the working substance, and the amount of working substance which is desorbed during the desorption process. As shown in Figure 1, the condensate vessel is preferably positioned beneath the adsorbent vessel 4,

allowing gravity to aid the passage of condensate from the adsorbent vessel to the condensate vessel.

Once the working substance vapor has been desorbed from the adsorbent vessel 4 into the condensate vessel 6, the vacuum valve 20 is closed and both the condensate vessel 6 and the adsorbent vessel 4 are permitted to cool. In one embodiment, both the adsorbent vessel and the condensate vessel cool to room temperature, approximately 70°F. The cooling rate of the adsorbent vessel 4 may be accelerated by adding a cooling source 36. However, the cooling source is not required for operation of the apparatus 2. Examples of cooling sources include fans, water jackets and other thermal dumps. Though the cooling source shown in Figure 1 is external to the adsorbent vessel 4, it may also extend within the adsorbent vessel to more efficiently cool the adsorbent material 10 therein.

When the adsorbent vessel 4 and condensate vessel 6 have cooled, the adsorption refrigerator 2 is ready to begin the adsorption phase. The vacuum valve 20 is opened permitting fluid communication between the adsorbent vessel 4 and the condensate vessel 6, and providing an immediate, sudden cooling effect. The adsorbent material 10 adsorbs the liquid working substance 26, causing it to change phase from a liquid to a vapor and pass through the pipe 8, the perforations 12, the mesh cloth 14, and into the adsorbent material 10. As the liquid working substance passes from the liquid state to the vapor state, it extracts the heat of vaporization from the surrounding liquid working substance and from the condensate vessel 6 causing the water and condensate vessel to cool. As the condensate vessel 6 and its contents cool, the liquid working substance begins to form solid working substance 28. As the adsorption phase continues, the liquid working substance 26 disappears either because it is adsorbed by the adsorbent material 10 or because it turns entirely to solid 28.

Once the liquid working substance 26 has disappeared from the condensate vessel 6, adsorption continues as the solid working substance 28 sublimates directly to a vapor which is adsorbed by the adsorbent material 10. When the liquid 26 and solid 28 have been substantially completely adsorbed, the cycle is complete. The heat source is then reactivated, driving water vapor through the pipe 8 back into the

condensate vessel 6 to repeat the refrigeration cycle. As used herein, the term substantially completely adsorbed means that substantially all the working substance, whether liquid phase or solid phase, has been adsorbed to a vapor phase, and transferred from the condensate vessel 6 to the adsorbent vessel 4.

5 The capacity of the adsorbent material 10 (*i.e.*, the maximum amount of working substance it retains) relative to the amount of working substance in the apparatus 2 is an important feature of the invention. In one embodiment, the adsorbent material 10 is MOLSIV Type 13X zeolite manufactured by UOP Inc. of Des Plaines, Illinois, and the working substance is water. In this embodiment, the capacity of the adsorbent material 10 is set at a value such that the adsorbent material completely 10 adsorbs both the liquid water 26 and the ice 28. The volume of the adsorbent material 10 is selected based on the desired cooling load and rate to be 22 cubic inches (*i.e.*, 0.51 pounds). The working substance is selected to be 60 cubic centimeters of water, (*i.e.*, 28.5% of the weight of the adsorbent material 10), and the volume of the condensate 15 vessel 6 is sized to be equal to the volume of the working substance. The amount of water desorbed by the adsorbent material 10 is 20 cubic centimeters when the adsorbent material is heated to 250°F. The remaining 40 cubic centimeters of water remains in the adsorbent material 10 after desorption. With this combination, residual water in the condensate vessel 6 is completely frozen approximately 11 seconds after vacuum valve 20 20 is opened and the adsorptive phase of the cycle begins. With no direct working load applied to the system (*i.e.*, no source applying heat to the condensate vessel), the frozen residual is completely adsorbed by the adsorbent material 10 approximately 120-160 minutes later.

The adsorbent-to-working-substance ratios and temperatures selected 25 above were selected to provide the cooling times indicated. Other ratios and temperatures are possible which adsorb and desorb more of the total working substance. Such ratios will reduce the frequency with which the adsorbent material 10 must be desorbed.

As discussed above, the adsorbent material 10 is zeolite and the working 30 substance is water in one embodiment. Other working substances and other adsorbent

materials, which have an affinity for the working substances are possible as well. Such working substances include NH₃, H₂, S, N₂, CO₂, etc., as well as both fluoro, chloro, and hydrocarbons, and mixtures of the same. These substances have varying affinities for adsorbent materials, as discussed below. Other adsorbent materials include
5 molecular sieves, silicon gel, activated alumina and other similar sodalite type structures, including powders, pellets, particles, solid forms and gels of the same.

The external surface area of the adsorbent molecular sieve crystal is available for adsorption of molecules of all sizes, whereas, the internal area is available only to molecules small enough to enter the pores. The external area is only about 1%
10 of the total surface area. Materials which are too large to be adsorbed internally will commonly be adsorbed externally to the extent of 0.2% to 1% by weight. Molecular sieves are available in a wide variety of types and forms. By choosing the appropriate adsorbent and operating conditions, it is possible to adapt molecular sieves to a number
15 of specific applications. Not only will molecular sieves separate molecules based on size and configuration, but they will also adsorb preferentially based on polarity or degree of unsaturation. In a mixture of molecules small enough to enter the pores, the less volatile, the more polar or the more unsaturated a molecule, the more tightly it is held within the crystal.

For example, in one embodiment of the present invention, the working
20 fluid is a mixture of CO₂ and water. The CO₂ more easily vaporizes than does the water. At the beginning of the adsorptive phase of the cycle, the CO₂ immediately vaporizes providing an immediate cooling effect. The water vaporizes more slowly but over a long period of time, providing for a long-term cooling. The CO₂, in addition to providing for an immediate cooling effect, improves the heat transfer rate from the heat
25 source 18 to the adsorbent material 10, thereby reducing the time and energy required to desorb the adsorbent material. Substances such as nitrogen may be used in combination with water as well. The nitrogen provides thermal conductivity, increasing the efficiency with which heat may be transferred away from the adsorbent material during desorption. Because the adsorbent material 10 does not adsorb nitrogen as strongly as
30 water, the nitrogen does not prevent the adsorbent material 10 from adsorbing water.

In one alternate embodiment of the device illustrated in Figure 1, the vacuum valve 20 is eliminated. As a result, the adsorbent material continuously adsorbs the working substance and continuously rather than suddenly cools the condensate vessel and its contents.

5 In the embodiment illustrated in Figure 1, the diameter of the adsorbent vessel 4 is 2.4 times the diameter of the pipe 8; however, other pipe diameters and configurations are possible as well. For example, the portion of the pipe 8 which is positioned within the adsorbent vessel 4 may be divided into a plurality of smaller pipes, each with perforations 12 and mesh cloth 14. The increased number of pipes
10 increases the rate of vapor transfer between the adsorbent 10 and the condensate vessel 6.

As illustrated in Figure 1, the heat source 18 is located external to the adsorbent vessel 4, however other arrangements are possible. For example, the heat source 18 may be placed within the adsorbent vessel 18 so as to more efficiently heat
15 the adsorbent material 10. In one such embodiment, the heat source 18 includes a water resistant incalloy element, and the adsorbent material 10 is adhered directly to the element to provide an intimate bond for efficient heat transfer. In this embodiment, the incalloy, or other suitable material, is capable of being exposed to air without melting while under a heat load. The binder material may be polyphenylene sulfide (PPS) or
20 aluminum phosphate. Aluminum phosphate is advantageous as a binder because it adds structural strength by combining activated alumina and/or aluminum oxide with the zeolite and can be heated above 600°F. PPS does not add as much strength but does not require the addition of activated alumina or aluminum oxide, so that 100% of the adsorbent can be zeolite.

25 In one embodiment illustrated in Figures 12 and 13, the adsorbent material is in the form of machined adsorbent disks 50 which are stacked on a solid heating element 52 formed from a material such as incalloy, which can be electrically heated by applying a voltage to cables 53. Each adsorbent disk 52 has holes 54 which permit desorbed vapor to be passed between the adsorbent disks 50 and the pipe 8. The
30 adsorbent disks 50 may be machined to provide rough surfaces 55 which allow air to

pass between the adsorbent disks to cool or heat the adsorbent disks as desired. A heat transfer jacket 56 annularly surrounds the external surfaces of the adsorbent disks 50. The heat transfer jacket is connected to a heat exchange source 57 to vary the temperature of the adsorption vessel 4. A fluid 58 such as water passes between the 5 heat transfer jacket 56 and the heat exchange source 57 to transfer heat between the adsorbent disks 50 and the heat exchange source 57. The adsorbent disks 50 may be machined to any desired shape and may be stacked on heating elements 52 having varying lengths so as to fit within adsorbent vessels 4 having varying dimensions.

As shown in Figure 12, the heat exchange source 57 and heat transfer 10 jacket 56 may act to transfer heat to or from the adsorbent disks 50. When the heat exchange source 57 and heat transfer jacket act 56 to heat the adsorbent disks 50, they increase the rate at which the adsorbent disks desorb the working substance, reducing the time required to desorb the adsorbent vessel 4, thereby reducing overall cycle time. When the heat transfer jacket 56 and heat exchange source 57 act to cool the adsorbent 15 disks 50, they immediately quench the adsorbent disks, reducing the time required to cool the adsorbent disks prior to the next adsorption phase, again reducing overall cycle time.

In another embodiment illustrated in Figures 14 and 15, the adsorbent material 10 is in the form of powder or pellets. A heating element 300 formed from a 20 material such as incalloy passes through the adsorbent material 10 and is connected to the heat exchange source 57. The heating element 300 has an annular cavity 302 through which fluid 58 passes. The heat transfer jacket 56 is also coupled to the heat exchange source 57, and also contains fluid 58.

As shown in Figures 14 and 15, the pipe 8 is bifurcated into perforated 25 sections 310 and 312. The perforated sections 310 and 312 contain perforations 12 to permit vapor to pass between the adsorbent material 10 and the perforated sections, and mesh cloth 14 to prevent the adsorbent material from entering the perforated sections. Although two perforated sections 310 and 312 are shown in Figures 14 and 15, a greater 30 number of perforated sections is possible as well to maximize the rate of vapor transfer between the adsorbent material 10 and the perforated sections. As discussed above in

relation to the embodiment illustrated in Figures 12 and 13, the heat exchanger source 57, heat transfer jacket 56 and annular heating element 300 may act to heat or cool the adsorbent material 10. When hot fluid, such as water or other suitable fluid, is passed from the heat exchange source 57 through the heat transfer jacket 56 and through the annular cavity 302 and the heating element is heated with an electric current supplied through cables 53, the rate at which the adsorbent material 10 desorbs is increased, reducing the time required to prepare the adsorbent vessel 4 for adsorption. When cold fluid, such as water or other suitable fluid, is passed from the heat exchange source 57 through the heat transfer jacket 56 and through the annular cavity 302, the adsorbent material 10 is immediately quenched, further reducing the time required to prepare the adsorbent vessel 4 for adsorption after it has been heated and prior to desorption.

In another embodiment illustrated in Figure 2, the condensate vessel is replaced by a heat exchanger 37 which is positioned within an insulated box 38. The operation of the adsorbent vessel 4 is substantially the same as operation of the adsorbent vessel discussed above in relation to Figure 1. As the heat exchanger cools during the adsorption phase, it cools the box 38. The box 38 may then be used to store any items, such as foodstuffs, which require refrigeration. The heat exchanger 37 contains heat exchanger tubing 40 which serves the same purpose as did the condensate vessel 6 of Figure 1. However, the heat exchanger tubing 40 provides a greater heat transfer surface area than does the condensate vessel 6 and therefore more efficiently cools the box 38. The heat exchanger tubing 40 is oriented at a downward angle to take advantage of gravitational forces as the heat exchanger tubing is filled with condensate.

The heat exchanger tubing 40 is shown in greater detail in Figure 3. In this embodiment, the working substance is a material which expands when solidified, such as water. As seen in Figure 3, the heat exchanger tubing 40 contains a foam or other compressible material 42 which accommodates the expansion of the working substance 26 as it freezes. The freezing water exerts pressure on the walls of the heat exchanger tubing 40, creating a hoop stress, and on the compressible material 42. Because the compressible material 42 is more compressible than the walls of the heat exchanger tubing, it deforms thereby preventing the pressure from exceeding the hoop

strength of the heat exchanger tubing 40 as the working substance freezes completely. Once the working substance has completely frozen, it continues to sublime and be adsorbed by the adsorbent material 10 as discussed previously. As used herein, the hoop strength refers to the stress beyond which the walls of the heat exchanger tubing 5 40 or other vessel in which the compressible material 42 is placed burst.

In one embodiment, it is desirable to size and position the compressible material 42 in the heat exchanger tubing 40 to leave a flow area in the heat exchanger tubing adequate to permit the flow of working substance vapor through the heat exchanger tubing during adsorption. At the same time, it is desirable to provide 10 sufficient compressible material 42 so that the freezing working substance does not completely compress the compressible material 42 and then burst the heat exchanger tubing 40. Therefore, in one embodiment, the ratio of the working substance volume to compressible material 42 volume is selected such that when the working substance freezes and expands, compressing the compressible material 42, the combined pressure 15 exerted by the frozen working substance, any remaining liquid working substance, and the compressible material 42 is less than the hoop strength of the heat exchanger tubing 40. In one embodiment, the compressible material contains cells that are waterproof so that the compressible material does not absorb water.

In another embodiment, adjacent portions of the compressible material 20 42 may have a different shape and compressibility, depending on the flow distance between that portion and the adsorbent material 10 (Figure 1). For example, portions of the compressible material 42 that are distant from the adsorbent material 10 can be configured to fill the entire cross-sectional area of the heat exchanger tubing 40 when the compressible material is fully expanded, while portions of the compressible material 25 42 closer to the adsorbent material 10 can be configured to fill less than the entire cross-sectional area. The compressible material 42 can then compress under the pressure of the working substance when the working substance is desorbed into the heat exchanger tubing 40 from the adsorbent material 10, and expand when the working substance is adsorbed. By leaving space between the compressible material 42 and the walls of the 30 heat exchanger tubing 40 close to the adsorbent material 10, a fluid path through the

entire heat exchanger tubing 40 can be maintained even as the compressible material expands, allowing more of the working substance to be adsorbed.

In the embodiment illustrated in Figure 3, the heat exchanger tubing comprises a single section having openings 46 which communicate with the adsorbent vessel 4. Other embodiments are possible as well. For example, the heat exchanger tubing 40 may be divided into several lengths, each having openings 46 which communicate with the adsorbent vessel. Such an arrangement increases the exposure of the fluid within the heat exchanger tubing to the adsorbent vessel 4. In a further embodiment, the heat exchanger tubing 40 may be fitted with fins 48 which increase the rate of heat transferred from the box 38 to the heat exchanger tubing, thereby increasing the rate at which the box is cooled.

In one embodiment of the invention, the compressible material 42 has a triangular cross-sectional shape as is shown in Figure 4. This shape permits the working substance 26 to pass through the tube around the compressible material 42. This shape also forces the working substance 40 contained within the heat exchanger tubing 40 to the walls of the tubing for maximum heat transfer efficiency. Other shapes which serve to position the working substance at the walls for maximum heat transfer are possible as well. As is shown in Figure 5, notches 44 allow the working substance 26 to pass from one side of the compressible material 42 to the other, thereby enhancing the rate at which liquid and vapor pass through the tube 40. In this embodiment, the notches 44 are arranged in a helical pattern as shown in Figure 5 to permit the liquid and vapor to more easily pass from one side of the compressible material 42 to another without compromising the structure of the compressible material 42. The helical arrangement of the notches also serves to minimize the hoop stress on the heat exchanger tubing 40 created when the compressible material 42 is compressed.

Although the compressible material 42 is shown in Figure 3 positioned in the heat exchanger tubing 40, the compressible material 42 may be placed in any vessel which is subject to bursting when liquid contained therein freezes and expands. For example, the compressible material 42 may be placed in an outdoor water faucet to prevent the faucet from breaking when the ambient temperature falls below freezing. In

these embodiments, the compressible material 42 may have any shape conforming to the shape of the vessel in which it is positioned, and need not be triangular or elongate, as shown in Figures 3 and 4. The compressible material may be positioned within the vessel such that it is adjacent to a first wall of the vessel and spaced apart from a second 5 wall of the vessel. In this way, the compressible material acts to insulate the first wall of the vessel, and to position the working substance adjacent to the second wall of the vessel for maximum transfer of heat between the working substance and the second surface.

Compressible material pellets may be used in vessels where the vessel 10 shape does not easily accommodate a single piece of compressible material. Although the heat exchanger tubing 40 is typically made from a thin walled, rigid, thermally conductive material, the compressible material 42 may also be installed in a vessel having flexible walls. In this embodiment, both the vessel walls and the compressible material 42 flex when the liquid contained therein freezes. Other such applications of 15 the compressible material 42 will be known to those skilled in the art.

In another embodiment of the present invention, illustrated in Figure 6, two adsorbent vessels 4 are connected to the condensate vessel 6. Each adsorbent vessel 4 is operated in substantially the same manner as discussed previously, but the two adsorbent vessels are operated out-of-phase so that when one adsorbent vessel is 20 adsorbing working substance from the condensate vessel, the other adsorbent vessel is being heated by a heat source 18 and desorbing vapor and condensate into the condensate vessel 6. While the heated vessel is desorbing vapor, the vacuum valve 20 directly connected to the vessel is closed to prevent the condensate from being immediately adsorbed by the adjacent adsorbent vessel. Valve 21 is opened to permit 25 the condensate to condense in an accumulator 23 without disturbing the simultaneous adsorption conducted by the other adsorbent vessel 4. When desorption from the desorbing vessel is complete, the valve 20 associated with the desorbing vessel is opened, allowing the working substance to flow from the accumulator 23 into the condensate vessel 6. In one embodiment, the heat sources 18 and adsorbent vessels 4 30 are sized so that when one adsorbent vessel is completely desorbed, cooled, and ready

to adsorb, the other adsorbent vessel is saturated and ready to desorb. The roles of the vessels are then reversed; the formerly desorbing vessel adsorbs from the condensate vessel 6 and the formerly adsorbing vessel desorbs into the accumulator 23. Although two adsorbent vessels are shown in Figure 6, other configurations utilizing more 5 adsorbent vessels are possible as well. Such embodiments are advantageous because they eliminate the need to exactly match the desorption time for one vessel to the adsorption time of the other.

Figure 7 illustrates a continuous cycle using multiple adsorbent systems together. Each adsorbent vessel 4 is coupled to a separate heat exchanger 37 containing 10 heat exchanger tubing 40. As with the embodiment illustrated in Figure 6, the adsorbent vessels 4 are operated out-of-phase, so that when one adsorbing vessel 4 is adsorbing the working substance from the heat exchanger 37 to which it is connected, the other adsorbing vessel is desorbing the working substance to its heat exchanger. In this manner, the insulated box 38 may be maintained at a substantially constant 15 temperature.

The box 38 has an upper freezer portion and a lower refrigerator portion. The upper freezer portion contains a relatively high density of heat exchanger tubing per unit volume of the box to achieve the low temperatures typically required for freezing foodstuffs. The lower refrigerator portion contains a lower density of heat exchanger 20 tubing per unit volume of the box than does the freezer portion, and is suitable for maintaining foodstuffs at typical refrigerator temperatures above 32°F. Other embodiments employing more than two adsorbing vessels and heat exchangers are possible as well. Such embodiments are advantageous because they eliminate the need to exactly match the desorption time for one vessel to the adsorption time of the other.

25 Figure 8 illustrates an embodiment of the present invention in which two adsorbent vessels 60 and 62 are connected to condensing vessel 66. The flow of adsorbing vapor between the adsorbent vessels 60 and 62 and the condensing vessel 66 drives a turbine 68 located at the entrance 70 of the condensing vessel to provide power to the power transfer equipment 72. Valves 74 and 76 may be opened or closed as 30 desired to permit communication of one or the other of the adsorbent vessels 60 and 62

with the condensing vessel 66. Bypass valves 75, 76, 77 and 78 allow condensate to return to the condensing vessel 66 through accumulators 79 and 71.

In operation, adsorbent vessel 60 is in a fully saturated state and adsorbent vessel 62 is in a fully desorbed and charged state, valve 76 is opened, valve 5 74 is closed, valve 75 is closed and valves 77 and 78 are closed. In a typical installation, the flow rate of working substance during desorption is too low to generate power at the turbine 68. Therefore, when the first adsorbent vessel 60 is heated, vapor leaving the vessel is routed through the bypass pipe 64 around the turbine 68 and into the accumulator 79. The second adsorbent vessel 62 adsorbs vapor from the condensate 10 vessel 66, causing the vapor to pass through the turbine 68. As the vapor passes through the turbine 68, it rotates the turbine. The rotational motion of the turbine is transferred by power transfer equipment 72 using means known in the art, such as a tightly sealed shaft or an eddy current coupling. Once the second adsorbent vessel 62 is saturated with vapor and the first adsorbent vessel 60 is fully charged, the roles of the 15 vessels are reversed. Valves 75, 76 and 77 are closed, and valves 74 and 78 are opened. The first adsorbent vessel 60 adsorbs vapor from the condensate vessel 66, driving the turbine 68, while the second adsorbing vessel 62 desorbs vapor through the bypass pipe 65 into the accumulator 71.

Other applications of the adsorbent refrigerator device disclosed in the 20 present invention are possible as well. For example, the apparatus can be used to lower the cold side temperature of a Stirling engine, thereby increasing the efficiency of the engine. Figure 9 illustrates a basic regenerative Stirling engine cycle, as disclosed in U.S. Patent No. 5,456,076 which is incorporated in its entirety herein by reference. The basic Stirling engine cycle at a minimum comprises: a heat source 81 supplying heat 25 energy to a hot region 82, a heat sink 84 removing heat from a cold region 83, a thermally conductive gaseous working fluid 85 which transports heat energy between the hot cylinder region 86 and cold cylinder region 87, a displacer piston 88 reciprocating in a displacer cylinder 89 having a hot chamber 90 and a cold chamber 91, the hot and cold chambers being connected by a thermally insulated regenerative heat 30 exchanger 92, a power piston 93 reciprocating in a power cylinder 94, a means for

converting motion of the power piston into useful power such as a rotating crankshaft, and a means for controlling the timing of the movement of the displacer relative to the power piston. The power piston 93 and displacer piston 88 may be free floating, as in a free floating Stirling linear generator, or mechanically connected. In this embodiment, 5 the heat source 81 includes an adsorption vessel, and the heat sink 84 includes a condensate vessel of the type previously discussed. The adsorption vessel and condensate vessel heat and cool the heat source 81 and heat sink 83, respectively, increasing the engine efficiency. In addition, the regenerative heat exchanger 92 may be replaced with an adsorbent vessel/condensate vessel combination of the type 10 previously discussed. The heat source 81 may include solar energy, so that during the day, the heat source heats adsorbent material, charging the adsorbent vessel. At night the adsorbent vessel adsorbs the working substance from the condensate vessel, heating the adsorbent vessel and cooling the condensate vessel. In this manner the inclusion of the adsorbent vessel and condensate vessel serves to store solar energy and keep the 15 Stirling engine operating, even at night.

In still a further embodiment, a carbon fiber or carbon foam material can be added to the hot region 82. As is discussed in greater detail below with reference to Figures 25-27, the carbon material may be highly thermally conductive to transfer heat to the working fluid 85. The carbon material may also be highly porous to increase the 20 thermal contact with the working fluid 85 and may be heated by applying an electric current thereto (in the case of carbon fiber) or by convective or conductive heat transfer (in the case of either the carbon fiber or the carbon foam). The carbon material can also act as a regenerator by extracting heat from the working fluid 85 when it passes from the hot region 82 to the heat sink 84. In another aspect of this embodiment, the carbon 25 material can adsorb moisture from the working fluid 85 when the working fluid passes in one direction, and can desorb the moisture to the working fluid when the working fluid passes in the opposite direction, further improving the efficiency of the Stirling engine. The Stirling engine can be of any type including a type that utilizes ferroelectric wafers, as disclosed in pending U.S. Patent Application No. 08/840,111 30 assigned to the National Aeronautics and Space Administration and incorporated herein

by reference. The heat sink 84 may include a carbon foam material that, by virtue of its high porosity and thermal conductivity, increases the heat extraction from the working fluid 85.

In another alternate embodiment of the invention, the adsorptive refrigerator may be used to improve the efficiency of thermal voltaic cells. The adsorptive refrigerator is used to reduce the cold side temperature of the voltaic cells and therefore increase the voltage output. Further embodiments are possible as well. For example, the heat transfer apparatus may be used to cool a flat plate used for fish processing, or to cool computer chips, power substations or cars. In each embodiment, relatively low grade heat which is readily available is used to generate the desired cooling effect.

Figure 10 illustrates an embodiment of the invention in which first and second adsorbent vessels 4 and 104 operate with a single condensate vessel 6 to cool a computer chip 180. While the first adsorbent vessel 4 is desorbing to an accumulator 23 with valve 21 open and bypass valve 27 and vacuum valve 20 is closed, the second adsorbent vessel 104 is adsorbing from the condensate vessel 6 with vacuum valve 120 and valve 121 closed and bypass valve 127 open. When the second adsorbent vessel 104 has completed adsorption and the first adsorbent vessel 4 has completed desorption, the positions of the valves are reversed and adsorbent vessel 4 begins to adsorb as adsorbent vessel 104 desorbs into the accumulator 123. In this way, the computer chip 180 is continuously cooled.

In the embodiment drawn in Figure 10, the computer chip 180 is positioned on a conduit between the condensate vessel 6 and the bypass valves 27 and 127. In another embodiment, the computer chip 180 can be positioned within the conduit or within the condensate vessel 6. In still a further aspect of this embodiment, a plurality of computer chips 180 can be placed on a substrate within the conduit or the condensate vessel 6. Each computer chip 180 can be attached to a section of a carbon fiber material, or other conductive material, and selectively heated, as necessary, to keep the computer chips at approximately the same temperature, thus preventing the substrate from fracturing as a result of differential thermal expansion. The carbon fiber

material is discussed in greater detail below with reference to Figures 25-31. In still a further aspect of the embodiment, the computer chips 180 can be sprayed with the working substance as it leaves the condensate vessel 6 during adsorption, to provide a direct cooling effect.

5 Figure 11 illustrates an alternate embodiment of the present invention in which the adsorbent vessel may be heated by a gas burner assembly 201 which exhausts through gas port 202 or an electric heater element 203 or by hot gas or liquid which flows in through inlet port 212 and out through outlet port 214. The method of heating the adsorbent material 10 contained in the adsorbent vessel 4 may be chosen based on
10 the availability of the heating source at the time of desorption. The inlet port 212 and outlet port 214 may be connected to any convenient heat source, such as a car radiator. A cooling heat exchanger 210 is also provided to reduce the temperature of the adsorbent vessel 4 once it has been desorbed. An entry port 205 is supplied to permit maintenance of the adsorbent vessel 4 and its controls 207. Vacuum port 32 is
15 connectable to a vacuum source (not shown) for evacuation of the adsorbent vessel to pressures less than atmospheric pressure.

Figure 16 illustrates an alternate embodiment of an apparatus in accordance with the invention. As shown in Figure 16, the adsorbent vessel 4 of an apparatus 400 is coupled to the heat exchanger 37 with the pipe 8 which passes through
20 the aperture 9 located in the base of the adsorbent vessel. The adsorbent vessel 4 is packed with adsorbent material 10 such as zeolite which has a strong affinity for polar working substances. The pipe 8 extends into the adsorbent vessel 4 and is surrounded by the adsorbent material 10. As discussed previously with reference to Figure 1, the pipe 8 contains perforations 12 which permit vapor to pass back and forth between the
25 adsorbent material 10 and the pipe. A mesh cloth 14 covers the perforations 12 and prevents adsorbent material 10 from entering the pipe through the perforations. A separator 430 is connected to the pipe 8 between the adsorbent vessel 4 and the heat exchanger 37 to separate the working substance as it passes from the heat exchanger to the adsorbent vessel.

The heat exchanger 37 includes an adsorption conduit 440, which is coupled at one end to the heat exchanger tubing 40 extending out of the refrigerated enclosure 38 and is coupled at an opposite end to an inlet port 432 of the separator 430. In a preferred embodiment, a thermal coupling 441 is positioned between the adsorption conduit 440 and the heat exchanger tubing 40 to substantially prevent conductive heat transfer between the walls of the adsorption conduit and the walls of the heat exchanger tubing. Such heat transfer could result in undesirably heating the heat exchanger tubing when the adsorbent vessel 4 is desorbed. In one embodiment, the thermal coupling is a length of silicon tubing. In other embodiments, any material which is thermally insulative and can withstand the pressures and temperatures within the apparatus 400 may be used.

A valve 424 is positioned in the adsorption conduit 440 to open or close fluid communication between the adsorption conduit and the separator 430. The separator contains an outlet port 434, which is coupled to the pipe 8 extending into the adsorbent vessel 4. A valve 420 is positioned to open or close fluid communication between the pipe 8 and the outlet port 434.

The separator 430 extracts at least a part of the working substance as the working substance passes in a fluid stream out of the heat exchanger 37 and toward the adsorbent vessel 4. The fluid stream may comprise gases and/or liquids. In one embodiment, the separator 430 is a centrifugal device, such as an Eliminex® separator manufactured by Reading Technologies, Inc. (Reading, Pennsylvania), though in other embodiments, other separator devices may be used. In the preferred embodiment, the separator 430 has a substantially circular cross-sectional shape. A baffle device 444 is centered within the separator 430 and coupled to the outlet port 434. An annular gap 442 is positioned between the baffle device 444 and an interior wall 446 of the separator. The fluid stream, which includes the working substance vapor, enters the inlet port 432 tangentially and swirls downward in an arcuate path through the gap 442 toward a liquid collection port 436. As the stream swirls through the gap 442, working substance vapor is centrifugally forced outward so as to collect in the form of droplets on the inner wall 446 of the separator. The droplets run down the wall 446 to the liquid

collection port 436. The stream then turns upward into the baffle 444 toward the outlet port 434. As the stream turns, working substance again precipitates from the stream and collects in the liquid collection port 436. The stream then passes through the outlet port 434 into the pipe 8 and into the adsorbent vessel 4.

5 The liquid collection port 436 is connected to a collection conduit 450 which is in turn connected to a condensing conduit 448. A valve 452 is positioned in the collection conduit 450 to regulate fluid flow therethrough. A cooling source 36a may be used to cool the liquid collected in the conduit before it is returned to the heat exchanger 37. In another embodiment, the cooling source 36a or a separate cooling 10 source may be used to cool the separator 430 and particularly the inner wall 446 of the separator. By cooling the separator 430, the temperature difference between the separator and the working substance is increased, increasing the likelihood that the working substance will condense on inner wall 446. This arrangement thus provides another means, in addition to centrifugal force, by which to separate the working 15 substance from the stream. In a further aspect of this embodiment, the adsorption conduit may also be cooled to enhance condensation of the working substance, and removal of the working substance from the fluid stream. A valve 422 may be closed to prevent liquid contained in the condensing conduit 448 from being adsorbed through the pipe 8 and into the adsorbent vessel 4. A return conduit 438 connects the 20 condensing conduit 448 to the heat exchanger tubing 40 to return liquid collected at the collection port 436 to the heat exchanger 37. A thermal coupling 441a is positioned between the heat exchanger tubing 40 and the return conduit 438 to prevent undesirable heat transfer between the tubing and the conduit. A valve 426 in the return conduit prevents fluid being adsorbed from the heat exchanger 37 from passing through the 25 return conduit 438 and bypassing the inlet port 432.

Although the cooling source 36a is shown schematically as a fan in Figure 16, other devices may be used to cool the liquid in the condensing conduit 448. In one such embodiment, the condensing conduit 448 is used to heat a thermal voltaic cell, causing the condensing conduit to cool as it heats the thermal voltaic cell. In

another embodiment, the condensing conduit 448 is used to heat the heat source of a Stirling engine (Figure 9).

In operation, the adsorbent vessel 4 cycles between an adsorption phase and a desorption phase as discussed previously with reference to Figure 1. When the 5 adsorbent vessel 4 has been desorbed and is ready for use, the valves 422 and 426 are closed and the valves 420 and 424 are opened. The fluid stream, which includes the working substance vapor, passes from the heat exchanger 37 through the adsorption conduit 440 and into the separator 430 through the inlet port 432. The vapor is removed from the fluid stream in the separator 430, collects at the liquid collection port 436 and 10 enters the condensing conduit 448. After having lost a portion of the working substance, the fluid stream passes through the outlet port 434 into the pipe 8 and into the adsorbent vessel 4. When the adsorption reaction has continued to a selected point, the valves 420 and 424 are closed to prevent the adsorbent material from adsorbing liquid contained in the separator 430 and the condensing conduit 448. In one 15 embodiment, the liquid contained in the condensing conduit 448 may be cooled with the cooling source 36a and returned via the return conduit 438 to the heat exchanger 37 by opening the valve 426. The liquid is then available for adsorption and additional cooling of the heat exchanger 37. The above cycle is repeated until the adsorbent material 10 is saturated. At that point, the heat source 18 is used to heat the adsorbent 20 vessel and desorb the vapors contained therein as discussed previously with reference to Figure 1. During the desorption, the valve 422 is opened to allow the desorbed vapors to enter the condensing conduit 448 where they are cooled to liquid form by the cooling source 36a and returned to the heat exchanger 37 in preparation for the next cycle.

In one embodiment, the valves 420, 422, 424, and 426 are operated 25 manually. In another embodiment, the valves are computer controlled to open and close based upon how much of the adsorption cycle has been completed. In a further aspect of this embodiment, the valves may be positioned on a manifold, such as a KIP Jr. manifold manufactured by Kip Inc. (Farmington, Connecticut). The valves may be controlled by any number of inputs. In one embodiment, the valves are controlled to 30 permit adsorption to occur for a specified period of time. In another embodiment, the

valves are controlled to permit adsorption to continue until a selected temperature is attained within the insulated box 38. In yet another embodiment, the valves are controlled to open or close when a selected amount of water or other working substance is collected at the liquid collection port 436 and in the condensing conduit 448. Other 5 control inputs may be used in other embodiments. In each embodiment, the valves are controlled to permit vapor to be adsorbed from the heat exchanger 37 until the selected state is attained. At that point, the valves are positioned to prevent further adsorption so as to prevent further vapor from reaching the adsorbent material 10. In this way, the adsorbent capacity of the adsorbent vessel 4 is effectively preserved, extending the 10 period of time during which the adsorbent material 10 is available for adsorption.

An advantage of the apparatus 400 shown in Figure 16 is that the separator 430 reduces the amount of working substance actually adsorbed by the adsorbent material 10 in the adsorbent vessel 4. Instead of being adsorbed, a portion of the working substance removed from the heat exchanger 37 is collected at the liquid 15 collection port 436. In this way, the capacity of the adsorbent material 10 is effectively increased. An amount of working substance is removed from the heat exchanger 37 causing the heat exchanger and the enclosure 38 in which it is housed to cool, but without causing the removed working substance vapor to attach to the adsorbent material 10. The adsorbent material can therefore continue to remove working 20 substance remaining in the heat exchanger 37 without becoming saturated, thereby increasing the length of time between desorption cycles.

In another embodiment of the present invention, illustrated in Figure 17, first and second heat exchangers 37a and 37b are coupled to a single adsorbent vessel 4. The heat exchangers 37a and 37b are each operated in substantially the same manner as 25 discussed previously with reference to Figure 16, but the two heat exchangers are operated out-of-phase so that when working substance is being adsorbed from one heat exchanger, condensed working substance is being cooled in preparation for return to the second heat exchanger.

In operation, the adsorbent vessel 4 is desorbed, as discussed previously 30 with reference to Figures 1 and 16. Valves 420 and 424a are opened to permit a fluid

stream containing working substance vapor to pass from the first heat exchanger 37a through the adsorption conduit 440a and into the separator 430. Liquid working substance is collected at the liquid collection port 436 and passes into a collection conduit 450. A valve 452 may be opened to permit the liquid to pass into the condensing conduit 448. The fluid stream, after having lost a portion of the working substance contained therein, passes through the outlet port 434 into the pipe 8 and into the adsorbent vessel 4. The valves 452, 420 and 422 may be closed to prevent liquid in the condensing conduit 448 from being adsorbed into the adsorption vessel 4.

At this point, adsorption from the first heat exchanger 37a is halted and adsorption from the second heat exchanger 37b is initiated. Valve 424a is closed and valve 424b is opened. Valve 420 is opened to permit adsorption from the second heat exchanger 37b. Working substance is separated from the fluid stream exiting the second heat exchanger 37b and the separator 430 and allowed to pass into the collection conduit 450. At the same time, liquid collected in the condensing conduit 448 from the first heat exchanger 37b may be cooled with the cooling source 36a. When a sufficient quantity of working substance has been adsorbed from the second heat exchanger 37b, the valve 424b is closed. Liquid contained in the condensing conduit 448 may be returned to the heat exchanger 37a and liquid collected from the heat exchanger 37b may be allowed to drain into the condensing conduit 448 by opening the valve 452. The liquid contained in the condensing conduit 448 may then be cooled while working substance is again desorbed from heat exchanger 37a. In this way, working substance is alternately removed from heat exchangers 37a and 37b until the adsorbent vessel 4 is saturated, at which time the adsorbent vessel is desorbed in a manner substantially similar to that discussed with reference to Figure 1. Although two heat exchangers are shown in Figure 17, other configurations utilizing more heat exchangers are possible as well. Further embodiments also include multiple adsorbent vessels 4 which permit one adsorbent vessel to be desorbed while the other is adsorbing as discussed previously in reference to Figure 6. Further embodiments also include a plurality of separators 430.

An advantage of the embodiment shown in Figure 17 is that adsorption of the working substance from within the enclosure 38 is continuous or nearly

continuous by cycling between a plurality of heat exchangers. In this way, the enclosure 38 is more easily maintained at a desired temperature.

Figure 18 illustrates an alternate embodiment of the present invention in which a heat transfer apparatus 500 includes an adsorbent vessel 504 having a heat transfer conduit 560. The adsorbent vessel 504 is coupled to the heat exchanger 37 positioned within the insulated enclosure 38. The adsorbent vessel 504 and heat exchanger 37 form a sealed enclosure containing a working substance therein, as described previously.

The adsorbent vessel 504 contains adsorbent material 10 such as zeolite which is introduced into the adsorbent vessel through an aperture 515 sealed with a plug 516. The heat transfer conduit 560 extends through the adsorbent vessel 504 such that the adsorbent material 10 is positioned between the heat transfer conduit 560 and the outer walls of the adsorbent vessel 504. The heat transfer conduit 560 is in close thermal contact with the adsorbent material 10 to allow heat to be easily transferred between the heat transfer conduit and the adsorbent material.

In one embodiment, the heat transfer conduit 560 contains an electrical heating unit 562. In a preferred aspect of this embodiment, the electrical heating unit 562 comprises conductive nickel chromium alloy coils 564 which pass through the heat transfer conduit 560 and are supported therein by insulative disks 566. The insulative disks 566 contain apertures 567 through which the conductive coils 564 pass. Such an electrical heating unit 562 is available from Process Heating Company (Seattle, Washington). The electrical heating unit 562 is connected to a power source 568. Power is applied to the electrical heating unit 562 to heat the adsorbent material 10 to desorb the adsorbent vessel 504.

The heat transfer conduit is preferably positioned closer to a lower wall 580 of the adsorbent vessel 504 than to an upper wall 582. In this way, heat which tends to rise from the heat transfer conduit 560 will tend to heat a greater portion of the adsorbent material 10 within the adsorbent vessel 504. In one embodiment, the heat transfer conduit 560 is coupled to an air inlet duct 570 which supplies cooling air to cool the heat transfer conduit 560 after desorption. Cool air is forced through the air

inlet duct 570 with a cooling source 36b to cool the heat transfer conduit 560, electrical heating unit 562, and adsorbent material 10. The cooling source 36b may comprise a fan or other such device. In a preferred embodiment, the air inlet duct 570 is coupled with a removable coupling 572a to the heat transfer conduit 560. In this way, the air inlet duct 570 can be easily removed from the heat transfer conduit 560 to access the electrical heating unit 562 for maintenance and/or replacement. The heat transfer conduit 560 is connected to an air exhaust duct 574 which conducts the cooling air away from the adsorbent vessel 504 after having passed through the heat transfer conduit. In a preferred embodiment, the air exhaust duct 574 is coupled with a removable coupling 572b to the heat transfer conduit 560 to permit easy access to the electrical heating unit 562.

In a preferred embodiment, the adsorbent vessel 504 includes an inner heat transfer tube 576a and an outer heat transfer tube 576b. The heat transfer tubes 576a and 576b are used to enhance heat transfer from and/or to the adsorbent vessel 504. In the preferred embodiment, the heat transfer tubes 576a and 576b are coupled to a source of cooling water (not shown) to cool the adsorbent material 10 within the adsorbent vessel 504 after desorption has been completed. In a preferred aspect of this embodiment, water is used as the cooling liquid, though in other embodiments other liquids or gases are used. When used as a cooling liquid, the water is preferably removed from the heat transfer tubes prior to desorption, so that heat intended to desorb the adsorbent vessel does not instead heat the water in the heat transfer tubes. The water removed from the heat transfer tubes, which is warmed as a result of cooling the adsorbent material, may also be used to desorb the adsorbent material. In further embodiments, the inner and outer heat transfer tubes may be coupled to a source of hot fluid (not shown) to heat the adsorbent material 10 in order to expedite desorption.

In the preferred embodiment, the inner and outer heat transfer tubes 576a and 576b are coiled about the heat transfer conduit 560. In this way, the heat transfer tubes flex, rather than break, during the heating and cooling cycles which result when the adsorbent vessel 504 is alternately desorbed and cooled. As the heat transfer tubes 576a and 576b flex, they tend to move the adsorbent material 10 in their immediate

vicinity, opening small gaps and passageways which allow vapor to more easily desorb from the adsorbent material 10. In a preferred aspect of the embodiment, the inner heat transfer tube 576a is positioned proximate to the heat transfer conduit 560 to cool and/or heat the adsorbent material 10 in that region. The outer heat transfer tube 576b is 5 positioned a greater distance away from the heat transfer conduit 560 so as to cool and/or heat adsorbent material located a greater distance from the heat transfer conduit. In other embodiments, a greater or lesser number of heat transfer tubes is employed.

The adsorbent vessel 504 is coupled to a vacuum source 33 with a vacuum conduit 534. The vacuum source allows the pressure within the adsorbent 10 vessel 504 to be reduced, thereby increasing the efficiency of the adsorption process as discussed previously. The adsorbent vessel 504 is coupled to the heat exchanger 37 via an adsorption pipe 508 and a condensing pipe 509 as shown in Figure 18. A screen 584 is positioned between the lower wall 580 and the adsorbent material 10 to prevent the adsorbent material from entering the vacuum conduit 534, adsorption pipe 508, or 15 condensing pipe 509. The screen 584 is held above the lower wall 580 with standoffs 586.

The adsorbent vessel 504 is coupled to the heat exchanger 37 and separator 430 in a manner substantially similar to that discussed previously with reference to Figure 16. The adsorption pipe 508 is connected to the outlet port 434 of 20 the separator 430. The adsorption conduit 440 is connected to the inlet port 432. A condensing conduit 448 collects liquid from the liquid collection port 436 and returns the liquid to the heat exchanger 37 via a manifold 588. The condensing pipe 509 provides separate conduit between the adsorbent vessel 504 and the manifold 588 by which to return the desorbed working substance from the adsorbent vessel 504 to the 25 heat exchanger 37. Cooling sources 36 and 36a cool the working substance prior to its entry into the manifold 588 and heat exchanger 37. In an alternate embodiment a single cooling source is used to cool fluid in both the condensing conduit 448 and the condensing pipe 509. Valves 520, 522, 524, and 526 are positionable to alternately allow adsorption of the working substance from the heat exchanger 37 and the return of 30 condensed working substance to the heat exchanger 37.

In an embodiment of the apparatus 500 shown in Figure 18, the adsorption vessel 504 includes a circulation device 590 positioned in an upper portion of the adsorption vessel. the circulation device 590 circulates fluid (gaseous or liquid) around and through the adsorptive material 10 to enhance the rate at which the adsorptive material desorbs the working substance. The circulation device also improves adsorption by circulating adsorbed fluid through the adsorbing vessel 504. A protective screen 592 prevents the adsorptive material 10 from interfering with the operation of the circulation device 590. As shown in Figure 18, the circulation device 590 may be a fan with rotatable blades in one embodiment; in other embodiments, the circulation device may include other means for circulating fluid within the adsorption vessel 504.

Operation of the heat transfer apparatus 500 is substantially similar to the operation described with reference to the embodiment shown in Figures 1 and 16. The adsorbent vessel 504 is initially desorbed by heating the electrical heating unit 562 allowing vapor to pass through the condensing pipe 509 where it is cooled by the cooling source 36 before entering the manifold 588 through the valve 522. The circulation device 590 may be activated to enhance desorption. Once desorption is complete, cooling air is passed through the inlet duct 570 to cool the electrical heating unit 562, the heat transfer conduit 560, and the adsorbent material 10 positioned proximate to the heat transfer conduit 560. Cooling liquid is passed through the inner and outer heat transfer tubes 576a and 576b to provide additional cooling for the adsorbent material 10.

Once adsorption is complete, valve 522 is closed, valve 526 is closed, and valves 524 and 520 are opened. Working substance is adsorbed from the heat exchanger 37 through the adsorption conduit 440 and into the separator 430. Liquid working substance is separated from the fluid stream removed from the heat exchanger 37 and passes through the liquid collection port 436 and into the condensing conduit 448. The fluid stream continues through the separator 430, into the adsorption pipe 508 and into the adsorbent vessel 504. When a selected period of time has passed, valves 520 and 524 are closed to prevent adsorption from the condensing conduit 448 and

further adsorption from the heat exchanger 37. Liquid in the condensing conduit 448 is cooled with the cooling source 36a and may be returned to the heat exchanger 37 by opening valve 526. The cycle is repeated until a sufficient quantity of vapor has passed through the adsorption pipe 508 to saturate the adsorbent material 10, at which point the 5 adsorbent vessel 504 is desorbed as discussed previously.

As discussed previously, an advantage of the embodiment shown in Figure 18 is that the capacity of the adsorbent vessel 504 is extended by separating liquid working substance from the fluid evacuated from the heat exchanger before it reaches the adsorbent material 10. A further advantage of the embodiment shown in 10 Figure 18 is that the electrical heating unit 562 effectively heats adsorbent material 10 to quickly desorb the adsorbent vessel 504. The heat exchanger conduit 560 is advantageously configured to allow easy removal and/or maintenance of the electrical heating unit 562. The inner and outer heat transfer tubes 576a and 576b effectively cool the adsorbent material 10 and may be used to supplement heating of the adsorbent 15 material 10 as well. The spiral shape of the heat transfer tubes 576a and 576b prevents the tubes from breaking or cracking under thermal stress and advantageously repositions the adsorbent material 10 within the adsorbent vessel 504 to allow the adsorbent material to be more easily desorbed. The air duct 570 supplies cooling air and allows the electrical heating unit 562 to be quickly cooled after desorption has been 20 completed, reducing the amount of time required to prepare the adsorbent vessel 504 for another cycle. Yet a further advantage of the embodiment shown in Figure 18 is that the circulation device 590 improves desorption and adsorption by circulating fluid through the adsorption vessel 504, increasing contact between the working substance and the adsorbent material 10 during adsorption, and increasing heat transfer from the 25 adsorbent material during desorption.

Figure 19 illustrates an alternate embodiment of the heat transfer conduit 560 shown in Figure 18. As shown in Figure 19, the heat transfer conduit 560 does not include an electrical heating unit 562 to heat the adsorbent vessel 504. Instead, the heat transfer conduit 560 is coupled to a hot air duct 570a and a cool air duct 570b. A valve

590 is positionable to allow fluid communication between the heat transfer conduit 560 and either the hot air duct 570a or the cool air duct 570b.

In one embodiment, the hot air duct 570a is coupled to the exhaust duct of an internal combustion engine, such as the exhaust pipe of an automobile or truck.

5 The cool air duct 570b is then coupled to an air scoop located on the vehicle to provide cool air to the heat transfer conduit 560.

Operation of the heat transfer apparatus 500 shown in Figure 19 is substantially similar to operation of the heat transfer operation shown in Figure 18. To desorb the adsorbent material 10 within the adsorbent vessel 504, the valve 590 is positioned as shown in phantom lines in Figure 19 to allow hot air from the hot air duct 570a to pass through the heat transfer conduit 560, heating the adsorbent material 10. When desorption is complete, the valve 590 is positioned as shown in solid lines in Figure 19 to allow cool air to flow from the cool air duct 570b into the heat transfer conduit 560 to cool both the heat transfer conduit and the adsorbent material 10 contained therein. Heating and cooling of the adsorbent material 10 is supplemented with the inner and outer heat transfer tubes 576a and 576b as discussed previously with reference to Figure 18.

An advantage of the embodiment of the heat transfer apparatus shown in Figure 19 is that it is particularly suitable for applications in which a source of hot and cool air is available, for instance vehicles such as cars or trucks. This application is particularly advantageous because it uses waste heat to desorb the working substance and air flowing past the vehicle to cool the adsorption vessel, both of which are readily available.

Figure 20 illustrates an alternate embodiment of a heat transfer apparatus 25 700 in which the heat exchanger is replaced with a hydrogen-oxygen fuel cell 737. The fuel cell 737 is connected to the adsorption conduit 440 which is in turn connected to the inlet port 432 of the separator device 430. The outlet port 434 of the separator device is connected to the pipe 8 which extends into the adsorbent vessel 4. Valves 420 and 424 positioned in the pipe 8 and the adsorption conduit 440 respectively control the 30 flow of working substance from the fuel cell 737 to the adsorbent vessel 4.

The liquid collection port 436 of the separator 430 is connected to the collection conduit 450 which is in turn connected to a wastewater conduit 748. The wastewater conduit is also coupled to the pipe 8 to receive desorbed working substance from the adsorbent vessel 4. The valve 422 regulates flow between the pipe 8 and the wastewater conduit 748. A dump valve 726 may be opened to remove water from the wastewater conduit 748. In one embodiment, the wastewater conduit 748 is coupled to a vacuum source 33a, communication with which is regulated by a valve 32a. The vacuum source permits evacuation of the wastewater conduit 748 and is preferred for systems which operate at less than atmospheric pressure. In other embodiments, such as systems which operate at or above atmospheric pressure, the vacuum source 33a is eliminated. In such embodiments, the vacuum source 33 may be eliminated as well.

10 The fuel cell 737 generates energy by combining hydrogen and oxygen. As a byproduct, the fuel cell 737 also generates water in the form of liquid and vapor. In one embodiment, the fuel cell is a type FC10K-NC fuel cell from Analytic Power Corp. (Boston, Massachusetts). In other embodiments, other types of hydrogen-oxygen fuel cells are used. The adsorbent vessel 4 removes the water by adsorption from the fuel cell 737 in a process substantially similar to that discussed with reference to Figures 1 and 16.

15 As the water, which is contained in a fluid stream, is adsorbed from the fuel cell 737, it passes through the separator 430 where a part of the water is removed from the fluid stream. The water exits the separator via the liquid collection port 436. The valve 452 may be opened to permit the water to flow through the collection conduit 450 and into the wastewater conduit 748 for cooling by the cooling source 36a. After draining the water from the separator 430, the valve 452 is closed.

20 Any water remaining in the fluid stream passes through the pipe 8 and is adsorbed by the adsorbent material 10. Once the adsorbent material 10, which is zeolite in one embodiment, has been saturated, it is heated with the heat source 18 to desorb the water contained therein. The desorbed water is completely removed from the system by opening the valve 422 to permit the desorbed vapor to enter the wastewater conduit 748. 25 The wastewater is then cooled by the cooling source 36a. Once desorption is complete,

valve 422 is closed to isolate the adsorbent vessel 4 and separator 430 from the wastewater conduit 748. The dump valve 726 is then opened to drain the water from the wastewater conduit. Once the water has drained from the wastewater conduit, the dump valve 726 is closed and the valve 32a is opened to permit the vacuum source 33a to evacuate the wastewater conduit 748. As discussed above, this step is necessary only where it is desired to maintain the system at or below atmospheric pressure. In a preferred embodiment, the evacuation is completed while the adsorption vessel 4 is being cooled with the cooling source 36. When the pressure within the wastewater conduit 748 is approximately equal to the pressure within the adsorbent vessel 4, and the adsorbent vessel is cooled, the heat transfer apparatus 700 is ready for another cycle. The combination of adsorbing water into the adsorbent vessel 4, desorbing the water from the adsorbent vessel, and removing water through the liquid collection port 436, removes water from the fuel cell 737.

An advantage of the embodiment of the heat transfer apparatus shown in Figure 20 is that the apparatus removes wastewater generated by the fuel cell. The water is typically in the form of a warm liquid or a vapor, and by removing the water from the fuel cell, the fuel cell is effectively cooled. As the fuel cell cools, its efficiency is increased, thereby increasing its power output. Furthermore, the heat transfer apparatus increases the efficiency of the membrane typically used in such fuel cells by removing moisture from the membrane. A further advantage of this embodiment of the heat transfer apparatus is that any remaining heat which is not removed from the fuel cell by removing the water therefrom may be used to supplement or replace the heat source 18 to desorb the adsorbent vessel 4. This is advantageous for two reasons. First, it reduces the power required to desorb the adsorbent vessel 4. Second, it further cools the fuel cell 737 which both increases the efficiency of the fuel cell and reduces the power required to cool the fuel cell. Yet a further advantage of an embodiment of the heat transfer apparatus which is maintained at less than atmospheric pressure is that by isolating the wastewater conduit 748 from the adsorbent vessel 4, the pressure in the adsorbent vessel is not substantially affected when the wastewater conduit is drained.

Figure 21 illustrates a further alternate embodiment of the heat transfer apparatus 400 in which the adsorbent vessel 4 includes at least one ferromagnetic member 810 positioned within the adsorbent vessel and proximate to the adsorbent material 10. In one embodiment, the ferromagnetic member 810 comprises annular disks 812 concentric with the pipe 8 and positioned along supports 814. In other embodiments, other shapes are used. In a preferred embodiment, the ferromagnetic member 810 comprises gadolinium. In other embodiments, the ferromagnetic member may comprise any ferromagnetic material or other material which exhibits a magnetocaloric effect, i.e., which has the property of heating up when placed in a magnetic field and cooling down when removed from the magnetic field. Magnetic characteristics of gadolinium are presented in an article entitled "The Ultimate Fridge Magnet," *The Economist*, April 19, 1997 at 81, incorporated herein by reference.

A magnet 816 is positioned external to the adsorbent vessel 4. In one embodiment, the magnet is cylindrical in shape and is concentric with the adsorbent vessel 4. The magnet 816 moves axially along the longitudinal rows of the adsorbent vessel 4. When the magnet 816 is positioned such that the ferromagnetic member 810 is within the magnetic field created by the magnet as shown in solid lines in Figure 21. The ferromagnetic member heats up, desorbing the working substance from the adsorbent material 10. When the magnet 816 is positioned such that the ferromagnetic member 810 is outside the magnetic field as shown in phantom lines, the ferromagnetic member cools, cooling the adsorbent material 10 in preparation for another adsorption cycle. In a preferred aspect of the embodiment, the walls of the adsorbent vessel 4 comprise a material that does not interfere with the magnetic field created by the magnet 816.

In an embodiment shown in Figure 21, a single magnet 816 is used to heat and cool the ferromagnetic member 810. In an alternate embodiment, a plurality of magnets 816 may be employed. In a further aspect of this alternate embodiment, the magnets may be movable relative to each other between a first position where the respective magnetic fields created by the magnets combine to create a stronger magnetic field to heat the ferromagnetic member 810, and a second position where the respective

magnetic fields cancel each other to cool the ferromagnetic member. In further alternate embodiments, the magnet 816 may move other than axially to create and remove the magnetic field. In still a further alternate embodiment, the magnet 816 may be an electromagnet. The electromagnet creates an electric field when electrical current is
5 passed therethrough, and the field is removed when the current flow ceases. In this way, the ferromagnetic member 810 is heated and cooled without moving the magnet 816. In yet a further alternate embodiment, a plurality of ferromagnetic materials, each capable of cycling between different temperature ranges is used to increase the heated temperature and/or decrease the cooled temperature of the zeolite.

10 An advantage of the ferromagnetic material is that it very quickly heats and cools the adsorbent material, reducing the time required to adsorb and cool the adsorbent vessel in preparation for another adsorption cycle. A further advantage of the ferromagnetic material is that it may reduce the power required to both heat and cool the adsorbent vessel 4.

15 In a further alternate embodiment of the invention, the magnet 816 may be moved by a mechanical device which is driven by a Stirling engine cycle. The mechanical device may be the power piston 93 or the displaced piston 88 (Figure 9). In yet a further alternate embodiment, the piston or other mechanical device may contain a ferromagnetic member and be proximate to a magnet such that when the piston moves
20 past the magnet, it is alternately heated and cooled, providing additional driving force to drive the Stirling cycle. In another embodiment, the piston contains a magnet and heats a ferromagnetic member positioned proximate to the cylinder in which the piston moves. The ferromagnetic member alternatively heats and cools the hot region 82 and cold region 83, respectively (Figure 9).

25 In still a further embodiment of the invention, shown in Figure 28, a ferromagnetic member 810a may be attached to a solid heat sink 820. The ferromagnetic member 810a may be a solid piece, or may include particles that are impregnated into the heat sink 820. The heat sink 820 may comprise any number of conductive materials, and in one embodiment, may include a carbon material, such as is
30 described in greater detail below with reference to Figures 25-27.

When the ferromagnetic member 810a is placed in a magnetic field, it tends to heat. The magnetic field may be generated by a magnetic source 815 that may include, for example, a conventional magnet, an electromagnet, an electrical device that generates a magnetic field, a superconducting magnet or other sources. The heat is conducted away from the ferromagnetic member 810a by the heat sink 820 until the ferromagnetic member cools to the ambient temperature. The ferromagnetic member 810a may then be further cooled by physically removing the ferromagnetic member from the magnetic field or by reducing the strength of the magnetic field. The cooling effect is then transmitted to the heat sink 820, which may be used to cool selected devices. For example, the heat sink 820 may cool the magnetic source 815. Alternatively, the heat sink 820 may be capable of adsorbing and desorbing a working substance and may be positioned in a sealed vessel to operate in a manner similar to the adsorbent material 10 described above with reference to Figure 21. In any case, the heating and cooling effect generated by the ferromagnetic member 810a may be increased by subjecting the ferromagnetic member to a strong magnetic field, for example, the magnetic field generated by a superconducting magnet.

Figure 22 illustrates an alternate embodiment of the heat exchanger tubing shown in Figure 16. As shown in Figure 22 the heat exchanger tubing 40a includes an outer container or conduit 600 and an inner container or conduit 610. The outer conduit 600 is substantially rigid and thermally conductive to provide effective heat transfer to and from the tubing 40a. The inner conduit 610 is preferably formed from a flexible material and is expandable between a contracted position shown in solid lines in Figure 22 and an expanded position shown in phantom lines. The inner conduit 610 is coupleable to a source of pressurized gas or liquid (not shown). In a preferred embodiment the working substance is contained within a channel 612 formed between the inner container 610 and the outer container 600. As the working substance begins to freeze during adsorption, the inner conduit 610 is inflated so as to force the frozen working substance toward an inner wall 614 of the outer container 600. In this way, the frozen working substance is in close contact with the outer container 600 and provides for maximum cooling of the region surrounding the heat exchanger tubing 40a, such as

the region within the insulated enclosure 38 (Figure 16). The inner container 610 can also flex inward so that if the working substance completely fills up the channel 612 as it freezes, the inner container 610 can compress and prevent the outer container 600 from bursting.

5 Figure 23 illustrates a further alternate embodiment of the heat exchanger tubing shown in Figure 22. The heat exchanger tubing 40b shown in Figure 23 comprises a rigid wall 620 connected to a flexible wall 622 to form an enclosed channel. The flexible wall 622 accommodates the expansion of the working substance contained therein as it freezes. In this way, the structural integrity of the heat
10 exchanger tubing 40b is not compromised as a result of the change in phase of the working substance contained therein.

15 Figure 24 illustrates an alternate embodiment of the heat exchanger shown in Figure 16. The heat exchanger 37 comprises two spaced-apart metal plates 620. A rubber gasket 621 is positioned between the metal plates and connected to both plates with a series of bolts 622. The bolts are positioned within the gasket 621 such that a head 624 of each bolt is captured within the rubber gasket 621 and a shank 626 of each bolt projects through a hole 628 in the metal plate 620. A nut 630 is threadably attached to the shank 628 to connect the bolt to the metal plate 620. As shown in Figure 24, the bolts do not pass entirely between the two metal plates, but rather alternately
20 connect the rubber gasket 621 to first one metal plate 620 and then the other. Holes are provided in the rubber gasket 621 to accommodate the adsorption conduit 440 and return conduit 438. In a preferred embodiment, the plates 620 are spaced close together to allow the working substance contained therein to be in close contact with the metal plates 620 when frozen so as to maximize the cooling effect provided by the heat
25 exchanger 37.

30 An advantage of the heat exchanger and heat exchanger tubing shown in Figures 22-24 is that the heat exchangers and tubing accommodate the expansion of the working substance as it freezes without causing the heat exchanger or tubing to break under stress. A further advantage of the embodiment shown in Figures 22-24 is that the heat exchangers and tubing allow the working substance contained therein to be

positioned closely to the heat exchanger surfaces increasing the cooling effect of the frozen working substance contained therein.

In still another embodiment of the invention, the adsorbent material shown in any of the foregoing figures may include carbon fibers, a network of carbon fibers, or a carbon foam material in addition to or instead of other adsorbent materials such as zeolite. In this regard, suitable materials are available from the U.S. Department of Energy, Washington, D.C., as described in pending U.S. Application No. 08/358,857 to Burchell et al., filed December 19, 1994, and pending U.S. Application No. 08/601,672 to Judkins et al., filed February 15, 1996 (both incorporated herein by reference). The carbon may be activated to have an affinity for water or other working substances, and may be housed in an adsorbent vessel. Where the carbon is in the form of a fiber, the carbon fiber may be coupled to a source of electric current to desorb water vapor from the carbon fiber. Desorption can be conducted without significantly raising the temperature of the carbon fiber. Desorption may be halted by removing the current source from the carbon fiber. Where the carbon is in the form of either a fiber or a foam, heat may be applied to the carbon to desorb the water vapor. The heat may be supplied from any source, including the sun. The desorbed water vapor may be collected in a separate condensate vessel and may be isolated from the carbon by closing a valve between the adsorbent vessel and the condensate vessel, as was generally described above with reference to Figure 1. When the valve is opened, the carbon tends to adsorb the water to freeze at least some of the water remaining in the condensate vessel. At least some of the frozen water may also be adsorbed by sublimation, as discussed above with reference to the foregoing figures, to create an additional cooling effect.

In one aspect of the embodiment discussed above, shown in exploded view in Figure 25, an apparatus 902 includes a vessel 904 having carbon fiber 910 disposed therein. The carbon fiber 910 is attached at each end to electrical contacts 911, one of which includes spikes or pins 913 at one end of the vessel 904 for heat transfer. A plate 915 is sealed to the opposite end of the vessel 904 and the vessel is evacuated except for a working substance, such as water. When current is applied to the electrical

contacts 911 by means of a current source 918, the working substance is desorbed from the carbon fiber 910 and collects on the inner surface 917 of the plate 915. Accordingly, the carbon fiber 910 is spaced apart from the inner surface 917 of the plate 915 to allow space for the working substance to accumulate. When the current is 5 removed, the working substance is adsorbed from the plate 915 to the carbon fiber 910 and the plate cools. The working substance may be adsorbed while it is in a liquid phase, and may continue to be adsorbed, by sublimation, once the working substance begins to solidify.

In one method of operation, adsorption may continue until the solidified 10 working substance is entirely removed from the plate 917, and in other methods, the adsorption may be stopped before the entire working substance is removed. In still further embodiments, the vessel 904 may include materials other than carbon fibers which behave in a similar manner when subjected to an electric current. In yet further embodiments, the working substance may include substances other than water, so long 15 as such substances can be desorbed from the adsorbent material when electrical current is passed therethrough and adsorbed by the adsorbent material when the current is removed.

As discussed above, the vessel 904 may be sealed and evacuated so as to undergo repeated adsorption/desorption cycles using the same working substance. In 20 another embodiment, the vessel 904 may be opened, for example, by removing either the contact 911 or the plate 915 to expose the carbon fiber 910. The carbon fiber 910 may then be used to adsorb moisture from the atmosphere and, when the vessel is re-sealed, desorbed, leaving water which may be used for drinking or other purposes.

In another embodiment, shown in Figure 26, a carbon fiber 910a may be 25 supplemented with zeolite. For example, the carbon fiber 910a may have openings 920 in the manner of a screen that contain zeolite pellets 921. This combination may be advantageous because the zeolite pellets 921 can adsorb the working substance relatively quickly, while the carbon fiber 910a (or alternatively, carbon foam), by virtue of its relatively high thermal conductivity, can desorb the working substance relatively

quickly and/or transfer heat to the zeolite pellets 921 to hasten the desorption of the zeolite pellets.

In still another embodiment, shown in Figure 27, the carbon fiber 910 can be activated to have an affinity for the working substance. For example, if the 5 working substance is water, the carbon fiber can be hydrophilic. The base 915 of the apparatus 902 can include a carbon foam material 924 activated to repel the working substance. For example, if the working substance is water, the carbon foam material 924 can be hydrophobic. Both the carbon foam material 924 and the carbon fiber 910 can be coated with a vacuum-tight coating 923 to form a sealed volume within which 10 the carbon foam material and the carbon fiber are in fluid communication. The coating may be formed from any suitable material, for example, a metal, or a copolyimide such as is disclosed in U.S. Patent No. 5,639,850 (incorporated herein in its entirety by reference) and available from Technature of Redmond, Washington. The working substance can be adsorbed and desorbed by the carbon fiber 910 in a manner generally 15 similar to that discussed above with reference to Figure 25 to cool the base 915. An advantage of this arrangement is that it may be easier to extract water from the hydrophobic carbon foam 924 than from a conventional heat exchanger during adsorption because the carbon foam 924 tends to repel the water.

As shown in Figure 27, the carbon fiber 910 is activated to have an 20 affinity for the working substance and the carbon foam material 924 is activated to repel the working substance. In other embodiments, the carbon fiber 910 can be activated to repel the working substance, the carbon foam material can be activated to have an affinity for the working substance, and the positions of the carbon fiber 910 and the carbon foam material 924 can be reversed.

25 Figure 29 is a cross-sectional view of an alternate embodiment of the heat exchanger tubing shown in Figure 22. As shown in Figure 29, the inner conduit 610 has a rod 613 disposed therein. The rod 613 can be slightly spaced apart from an inner wall of the inner conduit 610, as shown in Figure 29, or alternatively the rod 613 can be flush with the inner wall. The rod 613 may include a carbon fiber material 30 generally similar to that discussed above with reference to Figures 25-27. The rod 613

has an affinity for a pressurizing substance (for example, water) which is initially adsorbed by the rod 613. When an electric current passes through the rod 613, the rod desorbs the pressurizing substance, causing the pressurizing substance to move away from the rod and expand the inner conduit 610 toward the outer conduit 600. Once the 5 pressurizing substance has been completely desorbed, additional current can be applied to the rod 613 to heat the pressurizing substance, further expanding both the pressurizing substance and the inner conduit. When the current is removed, the rod 613 re-adsorbs the pressurizing substance, causing the inner conduit 610 to contract.

The pressurizing substance within the inner conduit 610 can be the same 10 as, or different from, the working substance positioned between the inner conduit 610 and the outer conduit 600, depending upon the adsorbent characteristics of the rod 613. For example, the rod 613 can be treated or activated to adsorb water in one embodiment and can be treated or activated to adsorb other substances in other embodiments.

In one embodiment, the expanding inner conduit 610 can be used to 15 move the working substance positioned between inner conduit 610 and the outer conduit 600 toward the outer conduit for improved heat transfer to the outer conduit, as was generally described above with reference to Figure 22. The inner conduit 610 can also be used to loosen or break up the working substance or other substances when the substances are frozen. In other embodiments, the rod 613 can displace any number of 20 substances, and can be used in a myriad of applications, some of which are described below.

Figure 30A is a partially broken side elevation view of a conduit 600 having a bladder valve 610a. The bladder valve 610a can be formed from a flexible, resilient material and is expandable between a contracted position, shown in solid lines 25 in Figure 30A, and an expanded position shown in phantom lines. In the contracted position, the bladder valve 610a is "open," i.e., the bladder valve allows fluid (liquid or gas) to move through the conduit 600. In the expanded position, the bladder valve 610a is "closed," i.e., the bladder valve seals against an inner wall 601 of the conduit 600 to prevent the motion of fluid through the conduit 600. The bladder valve 610a can also

be expanded to an intermediate position between the open and closed positions to restrict motion of the fluid through the conduit 600.

The bladder valve 610a can have a generally spherical shape, as shown in Figure 30A, or alternatively, the bladder valve can have any shape that fits within the conduit 600 and that can expand to block or at least restrict flow through the conduit. In any case, the bladder valve 610a can include a quantity of adsorbent material 613a that desorbs a pressurizing substance when subjected to an electrical current and adsorbs the pressurizing substance when the current is withdrawn, in a manner similar to that discussed above with reference to Figure 29. Accordingly, the bladder valve 610a can expand to the closed position when current is applied to the adsorbent material 613a and can contract to the open position when the current is released. An advantage of the bladder valve 610a is that it may have fewer moving parts than conventional valves and may accordingly last longer than conventional valves.

In still another embodiment of the invention, shown in Figure 30B, the conduit 600 can have a plurality of bladders 610b, each having a quantity of adsorbent material 613b disposed therein. The bladders 610b can be expanded and/or contracted sequentially to move a fluid through the conduit 600, as shown by arrow A. Accordingly, the bladders 610b may have a generally cylindrical shape in one embodiment, so that as the bladders expand, they tend to fill the conduit 600 and displace the fluid contained therein.

In yet another embodiment, shown in Figure 30C, the conduit 600 may include a plurality of adsorbent material pellets 613c, without any bladders. When an electrical current is passed through the adsorbent material pellets 613c, they desorb the pressurizing substance contained therein and displace the fluid contained within the conduit 600. Adjacent adsorbent material pellets 613c may be activated sequentially to pump the fluid through the conduit, in a manner generally similar to that discussed above with reference to Figure 30B. In one embodiment, the adsorbent material pellets 613c can be treated or activated to adsorb and desorb the same fluid as is pumped through the conduit 600. Alternatively, the pressurizing substance and the pumped fluid can be selected to be different, for example, when it is not detrimental for the

pressurizing substance to mix with the pumped fluid, or when the pressurizing substance and the pumped fluid tend not to mix.

In any of the foregoing embodiments discussed with reference to Figures 29-30C, the adsorbent material can include a carbon fiber, as was discussed above with reference to Figures 25-27, or any other material that can desorb a pressurizing substance when current is passed through the material and adsorb the pressurizing substance when the current is removed. The adsorbent material can be activated to adsorb and desorb water in one embodiment, or alternatively, the adsorbent material can be activated to adsorb and desorb any substance that can displace a bladder or a fluid when desorbed. The vessel within which the adsorbent material is disposed can include a conduit or any other type of container capable of retaining a liquid or gaseous fluid. Where the adsorbent material is used to pump a fluid, it can be selectively sized and shaped to achieve a desired flow rate.

The adsorbent materials discussed above with reference to Figures 1-30 can be assembled from smaller arrayable shapes. For example, as shown in Figure 31, an adsorbent material composite 930 may be formed by interconnecting several individual shaped portions 940 (two of which are shown in Figure 31), each having spaced apart plates or leaves 941 that interlock with the leaves of adjacent shaped portions, as described generally in pending U.S. Provisional Application No. 60/049,630, filed June 13, 1997, incorporated herein by reference. The shaped portions 940 may be connected to each other using mechanical fasteners or adhesives, or may remain connected due to frictional forces between the leaves 941. The shaped portions 940 may include a carbon foam material, a carbon fiber material, or other substances. For example, one of the shaped portions 941 may comprise copper and may be coupled to a source of electrical current to electrify the adjacent shaped portions. Such an arrangement may be suitable where the adjacent shaped portions 941 include a carbon fiber material that can be desorbed when an electrical current is applied thereto.

Each of the shaped portions 941 shown in Figure 31 has a generally hexagonal planform outline, so that the shaped portions form a generally gapless array when assembled. In other embodiments, the shaped portions 941 may have another

shape, for example, a triangular or rectangular shape, that also allows the shaped portions to be assembled without gaps therebetween. In still further embodiments, the shapes of the shaped portions 941 may be selected to leave gaps between the portions.

From the foregoing it will be appreciated that, although specific 5 embodiments of the invention have been described herein for purposes of illustration, various modifications may be made without deviating from the spirit and scope of the invention. Accordingly, the invention is not limited except as by the appended claims.

CLAIMS

I/We claim:

1. A heat transfer apparatus which uses a heat source to generate a cooling effect, the apparatus comprising:

a first vessel having a first aperture and containing an adsorbent material having an adsorbing capacity;

a second vessel having a second aperture, the second aperture connected to the first aperture of the first vessel with a conduit, the conduit providing a fluid passage between the vessels, the vessels and the conduit forming a sealed volume;

a quantity of working substance within the sealed volume, the working substance capable of being strongly adsorbed by the adsorbent material in a fluid stream as the working substance passes from the second vessel to the first vessel during adsorption of the working substance by the adsorbent material; and

a separator device connected in fluid communication with the conduit between the first and second vessels to separate at least a part of the working substance from the fluid stream.

2. The apparatus of claim 1 wherein the adsorbent material includes a carbon substance that can desorb the working substance when an electrical current is applied thereto and adsorb the working substance when the electrical current is removed.

3. The heat transfer apparatus of claim 1, further comprising a valve positioned in the conduit and moveable between an open position with the working substance free to move between the first and second vessels and closed position with the working substance constrained from movement between the vessels.

4. The heat transfer apparatus of claim 1 wherein the conduit is a first conduit further comprising a second conduit connecting the separator device to the second

vessel and providing a fluid passage between the separator device and the second vessel to return the part of the working substance removed the fluid stream to the second vessel.

5. The heat transfer apparatus of claim 1, further comprising a third vessel in fluid communication with the first vessel and the separator device wherein the part of the working substance is a first part and the fluid stream is a first fluid stream and the separator device is positioned to separate at least a second part of the working substance from a second fluid stream that passes from the third vessel to the first vessel.

6. The heat transfer apparatus of claim 5, further comprising a selector valve capable of movement between a first position in which the first fluid stream is free to move between the first and second vessels and a second position in which the second fluid stream is free to move between the first and third vessels.

7. The heat transfer apparatus of claim 1 wherein the second vessel comprises a refrigeration element for cooling a volume surrounding the second vessel.

8. The heat transfer apparatus of claim 1 wherein a portion of the working substance located in the second vessel is in a solid state and the solid state working substance sublimates to a vapor state and is substantially completely adsorbed by the adsorbent material.

9. The heat transfer apparatus of claim 1 wherein the quantity of working substance is not greater than the adsorbing capacity of the adsorbent material at a selected temperature and pressure of the sealed volume such that the working substance is capable of being substantially completely adsorbed by the adsorbent material.

10. The heat transfer apparatus of claim 1 wherein the separator device includes an arcuate flow path to centrifugally separate the part of the working substance from the fluid stream.

11. The heat transfer apparatus of claim 1, further comprising a cooling source positioned to cool the separator device to condense a portion of the working substance passing therethrough.

12. The heat transfer apparatus of claim 1, further comprising a heat source positioned proximate to the adsorbent material for heating the adsorbent material and evaporating the working substance therefrom, the heat source being controllable between an active state wherein the heat source heats the adsorbent material and an inactive state.

13. The heat transfer apparatus of claim 12 wherein the heat source is positioned within the first vessel.

14. The heat transfer apparatus of claim 1 wherein the adsorbent material is a zeolite.

15. The heat transfer apparatus of claim 1 wherein the working substance is water.

16. The heat transfer apparatus of claim 1 wherein the working substance is a first adsorbate, further comprising a second adsorbate, the first adsorbate being adsorbed by the adsorbent at a slower rate than a rate at which the second adsorbate is adsorbed by the adsorbent.

17. The heat transfer apparatus of claim 16 wherein the first adsorbate is water and the second adsorbate is carbon dioxide.

18. The heat transfer apparatus of claim 1 wherein the adsorbent is a first adsorbent and the working substance is a first adsorbate, further comprising a second adsorbent and a second adsorbate, the first adsorbate being adsorbed by the first adsorbent at a rate different than a rate at which the second adsorbate is adsorbed by the second adsorbent.

19. The heat transfer apparatus of claim 1 wherein the first vessel has a vacuum aperture therethrough and an internal pressure, further comprising a vacuum valve connected to the vacuum aperture, the vacuum valve connectable to a vacuum source and moveable between an open position with the vacuum source in fluid communication with the first vessel for reducing the internal pressure of the first vessel and a closed position with the first vessel sealed from the vacuum source.

20. The heat transfer apparatus of claim 1, further comprising a Stirling engine having an engine efficiency and operating between a hot reservoir and a cold reservoir wherein the second vessel is positioned to cool the cold reservoir, lowering a temperature at which the cold reservoir removes heat from the Stirling engine, and the first vessel and separator device are positioned to heat the hot reservoir, thereby increasing the engine efficiency relative to a Stirling engine lacking the heat transfer apparatus.

21. The heat transfer apparatus of claim 20, further comprising a piston movable within a cylinder toward and away from a magnet having a magnetic field, the piston comprising ferromagnetic material and increasing in temperature when positioned within the magnetic field and decreasing in temperature when positioned outside the magnetic field.

22. The heat transfer apparatus of claim 20, further comprising a piston movable within a cylinder, the piston comprising a magnet having a magnetic field and movable toward and away from a ferromagnetic material positioned external to the piston, the ferromagnetic material positioned external to the piston, the ferromagnetic material increasing in temperature when positioned within the magnetic field and decreasing in temperature when positioned outside the magnetic field.

23. A Stirling engine comprising:
a hot reservoir;
a cold reservoir;

a piston movable within a cylinder between the hot reservoir and the cold reservoir, the piston comprising ferromagnetic material; and

a magnet having a magnetic field and positioned external to the cylinder to heat the ferromagnetic material of the piston when the ferromagnetic material is positioned within the magnetic field and cool the ferromagnetic material of the piston when the ferromagnetic material is positioned outside the magnetic field.

24. A Stirling engine, comprising:

a hot reservoir;

a cold reservoir;

a piston movable within a cylinder between the hot reservoir and the cold reservoir, the piston comprising a magnet having a magnetic field; and

a ferromagnetic member comprising ferromagnetic material and positioned external to the cylinder to increase in temperature when the ferromagnetic material is within the magnetic field and decrease in temperature when the ferromagnetic material is outside the magnetic field.

25. The Stirling engine of claim 24 wherein the ferromagnetic member is positionable to heat the hot reservoir when the ferromagnetic material is within the magnetic field and cool the cold reservoir when the ferromagnetic material is outside the magnetic field.

26. The heat transfer apparatus of claim 1, further comprising a thermal voltaic device having a hot side and a cold side and a voltage output wherein the second vessel is positioned to cool the cold side, and the first vessel and separator device are positioned to heat the hot side thereby increasing the voltage output relative to a voltage device lacking the heat transfer apparatus.

27. The heat transfer apparatus of claim 1, further comprising a turbine device positioned in the conduit between the first and second vessels, the turbine device

having a turbine rotor capable of converting linear motion of the working substance as it is adsorbed by the adsorbent material from the second vessel to the first vessel to rotational motion and transferring energy associated with the rotational motion outside the conduit.

28. The heat transfer apparatus of claim 1 wherein the first and second vessels, conduit and working substance define a first refrigeration unit, further comprising at least a second refrigeration unit, the second vessels of the refrigeration units being contained within a refrigeration chamber defining a refrigerated volume, the refrigeration units being controllable to maintain the refrigerated volume at a selected temperature.

29. The heat transfer apparatus of claim 1, further comprising a refrigerator chamber defining an interior area having a temperature, wherein the second vessel is positioned within the interior area of the refrigerator chamber, the conduit passes through an aperture in the refrigerator chamber, and the first vessel is positioned outside the interior area, the heat transfer apparatus capable of lowering the temperature of the interior area below a temperature outside the interior area.

30. The heat transfer apparatus of claim 1 wherein the quantity of working substance is approximately equal to the adsorbing capacity of the adsorbent material.

31. The heat transfer apparatus of claim 1 wherein the conduit is a working substance conduit, further comprising a heat transfer conduit having a first end, a second end opposite the first, and an intermediate portion between the first and second ends and positioned within the first vessel adjacent to the adsorbent material.

32. The heat transfer apparatus of claim 31 wherein the heat transfer conduit has a first aperture toward the first end and a second aperture toward the second end, the first end being coupleable to a source of heated gas to heat the adsorbent material in the first vessel.

33. The heat transfer apparatus of claim 31 wherein the heat transfer conduit has a first aperture toward the first end and a second aperture toward the second end, the first end being coupleable to a source of gas to cool the adsorbent material in the first vessel.

34. The heat transfer apparatus of claim 31, further comprising an electrical heating element positioned within the heat transfer conduit to heat the adsorbent material in the first vessel.

35. The heat transfer apparatus of claim 34 wherein the electrical heating element is removably positioned within the heat transfer conduit.

36. The heat transfer apparatus of claim 1, further comprising at least one heat transfer tube having a first end, a second end and an intermediate portion, the intermediate portion extending into the first vessel adjacent the adsorbent material, the first end coupleable to a source of fluid to regulate a temperature of the adsorbent material in the first vessel.

37. The heat transfer apparatus of claim 36 wherein the first end of the heat transfer tube is coupleable to a source of cooled liquid to cool the adsorbent material.

38. The heat transfer apparatus of claim 36, further comprising a heat transfer conduit having a first end, a second end opposite the first, and an intermediate portion between the first and second ends and positioned within the first vessel adjacent the adsorbent material wherein the intermediate portion of the heat transfer tube forms a spiral around and external to the intermediate portion of the heat transfer conduit.

39. The heat transfer apparatus of claim 36 wherein the heat transfer tube is a first heat transfer tube and the source is a first source, further comprising a second heat

transfer tube extending into the first vessel and coupleable to a second source of fluid to regulate the temperature of the adsorbent material in the first vessel.

40. The heat transfer apparatus of claim 1, further comprising a circulation device positioned within the first vessel to circulate fluid within the first vessel and increase contact between the fluid and the adsorbing material.

41. The heat transfer apparatus of claim 40 wherein the circulation device includes a fan having fan blades rotatable relative to the first vessel.

42. The heat transfer apparatus of claim 1, further comprising a cooling source positioned to cool a portion of the conduit between the separator device and the second vessel to condense a portion of the working substance passing therethrough.

43. The heat transfer apparatus of claim 1 wherein the conduit has a first portion connected to the first vessel and a second portion connected to the second vessel, further comprising a thermal coupling connected between the first and second portions to permit fluid communication between the first and second portions and substantially prevent conductive heat transfer between the first and second portions.

44. The heat transfer apparatus of claim 1, further comprising:
a ferromagnetic member comprising a ferromagnetic material positioned within the first vessel proximate to the adsorbent material, the ferromagnetic member capable of increasing in temperature when placed in a magnetic field and decreasing in temperature when removed from the magnetic field; and
a magnet positionable proximate to the first vessel and capable of creating a magnetic field around the ferromagnetic member to heat the ferromagnetic member.

45. The heat transfer apparatus of claim 44 wherein the magnet is movable between a first position relative to the ferromagnetic member to create the magnetic field

around the ferromagnetic member and a second position relative to the ferromagnetic member to remove the magnetic field around the ferromagnetic member.

46. The heat transfer apparatus of claim 44 wherein the magnet is a first magnet, further comprising a second magnet, the first and second magnets movable relative to each other between a first position to create the magnetic field around the ferromagnetic member and a second position to remove the magnetic field.

47. The heat transfer apparatus of claim 44 wherein the ferromagnetic member is a first ferromagnetic member and the ferromagnetic material is a first ferromagnetic material, further comprising a second ferromagnetic member comprising a second ferromagnetic material.

48. The heat transfer apparatus of claim 44 wherein the magnet is an electromagnet capable of creating the magnetic field when electrical current is passed through the magnet and capable of removing the magnetic field when electrical current is not passed through the magnet.

49. The heat transfer apparatus of claim 44 wherein the magnet is coupled to a piston of a Stirling engine, the Stirling engine having an engine efficiency and operating between a hot reservoir and a cold reservoir wherein the second vessel is positioned to cool the cold reservoir, lowering a temperature at which the cold reservoir removes heat from the Stirling engine, and the first vessel and separator device are positioned to heat the hot reservoir, thereby increasing the engine efficiency relative to a Stirling engine lacking the heat transfer apparatus.

50. The heat transfer apparatus of claim 1 wherein the second vessel comprises:

a first container having substantially rigid walls; and

a second container positioned within the first container and having flexible walls expandable between a first state in which the flexible walls are a first distance from the rigid walls and a second state in which the flexible walls are positioned a second distance from the rigid walls, the second distance being less than the first distance to force the working substance positioned between the first container and the second container toward the rigid walls of the first container.

51. The heat transfer apparatus of claim 1 wherein the second vessel comprises:

a substantially rigid wall; and

a flexible wall connected to the substantially rigid wall, the flexible wall and the substantially rigid wall defining an interior volume capable of containing the working substance, the flexible wall displaceable between a first position in which a portion of the flexible wall is a first distance from the substantially rigid wall when the substance is in a liquid phase and a second position in which the portion of the flexible wall is a second distance greater than the first distance from the substantially rigid wall when the working substance changes phase from a liquid to a solid.

52. A vessel for containing a substance, comprising:

a first container having substantially rigid walls; and

a second container positioned within the first container and having flexible walls expandable between a first state in which the flexible walls are a first distance from the rigid walls and a second state in which the flexible walls are positioned a second distance from the rigid walls, the second distance being less than the first distance to force the substance positioned between the first container and the second container toward the rigid walls of the first container.

53. The vessel of claim 52 wherein the second container is coupleable to a source of pressurized gas, the gas being capable of expanding the second container from the first state to the second state.

54. A vessel for containing a substance which expands when changing phase from a liquid to a solid, comprising:

a substantially rigid wall; and

a flexible wall connected to the substantially rigid wall, the flexible wall and the substantially rigid wall defining an interior volume capable of containing the substance, the flexible wall displaceable between a first position in which a portion of the flexible wall is a first distance from the substantially rigid wall when the substance is in a liquid phase and a second position in which the portion of the flexible wall is a second distance greater than the first distance from the substantially rigid wall when the substance changes phase from a liquid to a solid.

55. The vessel of claim 54 wherein the substantially rigid wall is a first substantially rigid wall, further comprising a second substantially rigid wall spaced apart from the first, the flexible wall being interposed between and connected to the first and second substantially rigid walls.

56. The vessel of claim 55 wherein the first and second substantially rigid walls each include a flat plate, each flat plate having a perimeter portion extending around an outer edge of each flat plate, the flexible wall extending between and connected to the perimeter portions of the flat plates.

57. A heat transfer apparatus for removing heat and water from a hydrogen-oxygen fuel cell, comprising:

an adsorbent vessel containing an adsorbent material having an adsorbent capacity, the adsorbent vessel being coupleable to a hydrogen-oxygen fuel cell to remove by adsorption water produced by the fuel cell; and

a separator device connected in fluid communication with the adsorbent vessel and the fuel cell to separate at least a part of the water from a fluid stream that includes the water and passes from the fuel cell to the adsorbent vessel when the adsorbent material adsorbs the water.

58. The apparatus of claim 57 wherein the adsorbing material includes a carbon substance that can desorb the working substance when an electrical current is applied thereto and adsorb the working substance when the electrical current is removed.

59. The heat transfer apparatus of claim 57 wherein the adsorbent material is zeolite.

60. The heat transfer apparatus of claim 57, further comprising a vacuum source coupled to the adsorbent vessel to reduce an internal pressure of the adsorbent vessel.

61. The heat transfer apparatus of claim 57, further comprising a heat source positioned proximate to the adsorbent material for heating the adsorbent material and evaporating the water therefrom, the heat source being controllable between an active state wherein the heat source heats the adsorbent material and an inactive state.

62. The heat transfer apparatus of claim 57, further comprising a wastewater conduit for receiving water from the separator device, the wastewater conduit having a valve for regulating fluid communication between the wastewater conduit and the adsorbent vessel.

63. The heat transfer apparatus of claim 57 wherein the separator device includes an arcuate flow path to centrifugally separate the part of the water from the fluid stream.

64. A heat transfer apparatus, comprising:
a vessel having a first portion and a second portion, the first and second portions together defining a sealed volume;
a quantity of working substance within the sealed volume; and
a quantity of adsorbent material having an adsorbing capacity and being positioned in the first portion of the vessel, the adsorbent material being coupleable to a

source of electric current to desorb the working substance, the adsorbing capacity of the adsorbent material being sufficient to adsorb by sublimation at least part of the working substance when the working substance is in a solid state, substantially all the working substance remaining in the sealed volume after the at least part of the working substance has been adsorbed.

65. The heat transfer apparatus of claim 64 wherein the adsorbent material includes a carbon substance.

66. The heat transfer apparatus of claim 64 wherein the adsorbent material includes a carbon fiber.

67. The heat transfer apparatus of claim 64, further comprising a valve positioned between first and second portions to regulate fluid communication between the portions.

68. The heat transfer apparatus of claim 64, further comprising a source of electric current coupled to the adsorbent material to desorb the working substance from the adsorbent material.

69. A heat transfer apparatus, comprising:

a vessel having a first portion and a second portion, the first and second portions together defining a sealed volume;

a quantity of working substance within the sealed volume; and

a quantity of carbon adsorbent material having an adsorbing capacity and being positioned in the first portion of the vessel.

70. The heat transfer apparatus of claim 69 wherein the adsorbing capacity of the carbon adsorbent material is sufficient to adsorb by sublimation at least part of the working substance when the working substance is in a solid state, substantially all the

working substance remaining in the sealed volume after the at least part of the working substance has been adsorbed.

71. The heat transfer apparatus of claim 69 wherein the carbon adsorbent material includes a carbon foam.

72. The heat transfer apparatus of claim 69 wherein the carbon adsorbent material includes a carbon fiber.

73. The heat transfer apparatus of claim 69, further comprising a quantity of activated carbon material in the second portion of the vessel activated to repel the working substance.

74. The heat transfer apparatus of claim 73 wherein the vessel includes a coating on the carbon adsorbent material and the activated carbon material.

75. The heat transfer apparatus of claim 69, further comprising zeolite located in the first portion of the vessel.

76. The heat transfer apparatus of claim 69 wherein the adsorbing capacity of the heat conductive material is sufficient to adsorb by sublimation at least part of the working substance when the working substance is in a solid state, substantially all the working substance remaining in the sealed volume after the at least part of the working substance has been adsorbed.

77. A heat transfer apparatus, comprising:

a ferromagnetic material; and

a solid heat conductive material attached to the ferromagnetic material, the ferromagnetic material heating the conductive material when proximate a magnetic field and cooling the heat conductive material when spaced apart from the magnetic field.

78. The heat transfer apparatus of claim 77 wherein the ferromagnetic material includes gadolinium.

79. The heat transfer apparatus of claim 77 wherein the conductive material includes a carbon material.

80. The heat transfer apparatus of claim 77 wherein the conductive material has an adsorbent capacity, further comprising:

a vessel having a first portion and a second portion, the first and second portions together defining a sealed volume; and

a quantity of working substance within the sealed volume, the conductive material being positioned in the first portion of the vessel.

81. The heat transfer apparatus of claim 77, further comprising a magnetic field source.

82. The heat transfer apparatus of claim 81 wherein the magnetic field source includes a superconducting magnet.

83. A Stirling engine, comprising:

a hot reservoir;

a cold reservoir;

a piston movable within a cylinder between the hot reservoir and the cold reservoir to move a working fluid in the cylinder; and

a carbon material in thermal contact with the working fluid to transfer heat between the carbon material and the working fluid.

84. The Stirling engine of claim 83 wherein the carbon material includes a carbon fiber.

85. The Stirling engine of claim 84, further comprising a source of electrical current coupled to the carbon fiber to heat the carbon fiber.

86. The Stirling engine of claim 83 wherein the carbon material includes a carbon foam.

87. A displacement device, comprising:
a container having an inner surface; and
an adsorbent material disposed within the container, the adsorbent material desorbing a pressurizing substance when electrical current is applied to the adsorbent material to displace a fluid in the container, the adsorbent material adsorbing the pressurizing substance when the electrical current is removed.

88. The device of claim 87, further comprising a flexible bladder disposed about the adsorbent material and positioned within the container, the flexible bladder expanding to an expanded position when the desorbing material desorbs the pressurizing substance and contracting to a contracted position when the adsorbent material adsorbs the pressurizing substance.

89. The device of claim 88 wherein the container is a conduit having first and second adjacent portions and a cross-sectional area intermediate the first and second portions, the adsorbent material and the bladder being configured to fill the cross-sectional area and generally block fluid communication between the first and second portions when the bladder is in the expanded position.

90. The device of claim 87 wherein the container is a conduit having a fluid adjacent the inner wall and the adsorbent material is one of a plurality of adsorbent material portions, neighboring adsorbent material portions being configured to have an electrical current sequentially passed therethrough to displace the fluid through the conduit.

91. The device of claim 87 wherein the adsorbent material is selected to adsorb and desorb a pressurizing substance that is different than the fluid in the container.

92. The device of claim 87 wherein the adsorbent material is selected to adsorb and desorb a pressurizing substance that is generally similar to the fluid in the container.

93. The device of claim 87 wherein the adsorbent material includes a carbon fiber.

94. The device of claim 87 wherein the pressurizing substance includes water and the adsorbent material is treated to adsorb and desorb water.

95. A shaped carbon material assembly unit, comprising
a first carbon plate that includes carbon material; and
a second carbon plate that includes carbon material, the second carbon plate being connected to and spaced apart from the first carbon plate to form a receiving aperture between the first and second carbon plates sized to receive a plate having a thickness the same as a thickness of the first carbon plate, the first and second carbon plates having generally similar arrayable planform shapes so that the first plate of one carbon material assembly unit can be received by the receiving apertures of a plurality of adjacent carbon material assembly units to form an array of carbon material assembly units.

96. The carbon material assembly unit of claim 95 wherein the planform shape of the first and second carbon plates is hexagonal.

97. The carbon material assembly unit of claim 95, further comprising an electrically conductive assembly unit having first and second connected and spaced apart conductive plates, the first conductive plate being received in the receiving aperture between

the first and second carbon plates, the first and second conductive plates having a planform shape generally similar to the planform shape of the first and second carbon plates.

98. The carbon material assembly unit of claim 95 wherein the first carbon plate includes a carbon fiber material.

99. The carbon material assembly of claim 95 wherein the first carbon plate includes a carbon foam material.

100. A method for transferring heat and a working substance between a first vessel containing an adsorbent material and a second vessel connected to the first vessel, the two vessels defining a sealed volume containing a working substance in a liquid phase, the method comprising:

allowing a portion of the working substance to vaporize by adsorption and transfer out of the second vessel, thereby causing a remaining portion of the working substance to freeze, creating a frozen working substance; and

separating a first part of the portion of the working substance from a fluid stream that comprises the portion of the working substance.

101. The method of claim 100, further comprising continuing to adsorb the frozen working substance by sublimation out of the second vessel.

102. The method of claim 100, further comprising continuing to adsorb the frozen working substance by sublimation out of the second vessel until the frozen working substance is substantially completely removed from the second vessel.

103. The method of claim 100, further comprising adsorbing to the adsorptive material in the first vessel a second part of the portion of the working substance transferred out of the second vessel.

104. The method of claim 103, further comprising:
heating the adsorbent to drive the second part of the portion of the working substance contained therein in a vapor state from the adsorbent to the second vessel; and
condensing the working substance from a vapor state to a liquid state.

105. The method of claim 100, further comprising returning the first part of the portion of the working substance to the second vessel.

106. The method of claim 100, further comprising applying an electric current to the adsorbent material to desorb the working substance from the adsorbent material.

107. The method of claim 106, further comprising removing the electric current from the adsorbent material to adsorb the working substance.

108. A method for transferring heat and working substance between first and second portions of a sealed volume, the first portion having an adsorbent material, the method comprising:

applying an electric current to the adsorbent material to desorb the working substance from the adsorbent material; and

removing the electric current from the adsorbent material to adsorb the working substance to the adsorbent material.

109. The method of claim 108 wherein desorbing the working substance includes transferring the working substance from the first portion of the sealed volume to the second portion of the sealed volume.

110. The method of claim 108, further comprising closing a valve between the first and second portions of the sealed volume to isolate the portions from each other.

111. The method of claim 108 wherein adsorbing the working substance includes allowing a portion of the working substance to vaporize by adsorption and transfer to the adsorbent material, thereby causing a remaining portion of the working substance to freeze, creating a frozen working substance.

112. The method of claim 111, further comprising continuing to adsorb the frozen working substance by sublimation to the adsorbent material.

113. The method of claim 112 wherein continuing to adsorb the frozen working substance includes continuing to adsorb the frozen working substance until the frozen working substance is substantially completely adsorbed.

114. A method for collecting water vapor from the atmosphere, comprising:
exposing an adsorbent material having an adsorbing capacity to the atmosphere to adsorb water vapor from the atmosphere; and
desorbing the adsorbent material to release the water from the adsorbent material.

115. The method of claim 114 wherein desorbing the adsorbent material includes heating the adsorbent material.

116. The method of claim 114 wherein desorbing the adsorbent material includes applying an electric current to the adsorbent material.

117. A method for transferring heat, comprising:
positioning a ferromagnetic member proximate a magnetic field to heat the ferromagnetic member;
cooling the ferromagnetic member by conducting heat from the ferromagnetic member through a solid heat conductive material; and

further cooling the ferromagnetic member by removing the magnetic field from the ferromagnetic member.

118. The method of claim 117 wherein removing the magnetic field includes moving the ferromagnetic member relative to the magnetic field.

119. The method of claim 117 wherein removing the magnetic field includes changing the magnetic field from a first state to a second state to reduce the strength of the magnetic field.

120. A method for displacing a fluid in a container, comprising:
adsorbing a pressurizing substance to an adsorbent material within the container; and

applying an electrical current to the adsorbent material within the container to desorb the pressurizing substance from the adsorbent material and displace the fluid.

121. The method of claim 120 wherein desorbing the pressurizing substance includes expanding a flexible bladder disposed about the adsorbent material.

122. The method of claim 121 wherein the container includes a conduit and expanding the flexible bladder includes at least partially blocking the conduit with the bladder to at least restrict flow of the fluid through the conduit.

123. The method of claim 122 wherein expanding the bladder includes blocking flow of the fluid through the conduit.

124. The method of claim 120 wherein the container includes a conduit and the adsorbent material is one of a plurality of adsorbent material portions, further comprising sequentially applying an electrical current to neighboring adsorbent material portions to move the fluid through the conduit.

125. The method of claim 120, further comprising continuing to apply electrical current to the adsorbent material to heat the adsorbent material and expand the pressurizing substance.

126. The method of claim 120 wherein adsorbing the pressurizing substance to the adsorbent material includes removing the electrical current from the adsorbent material.

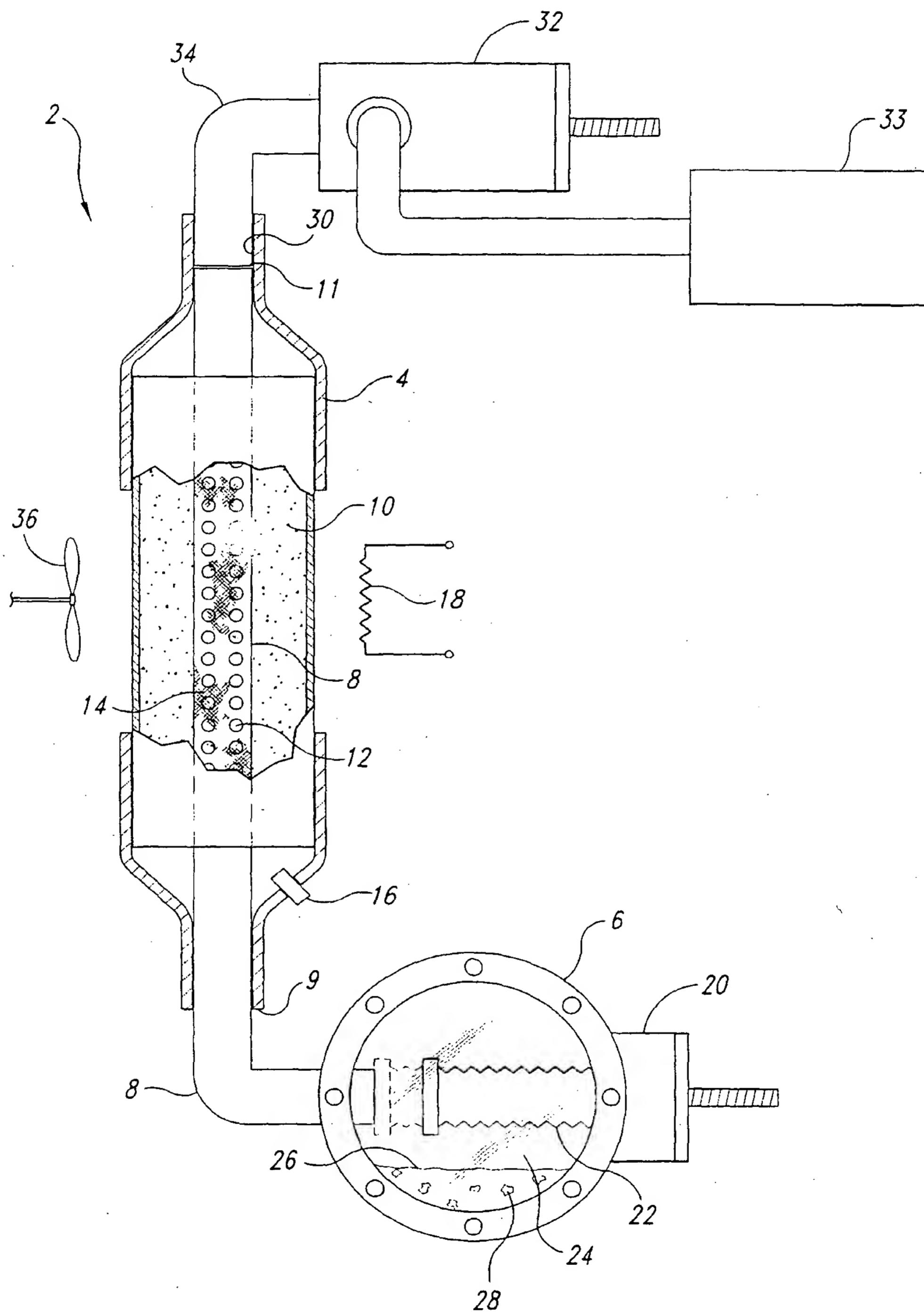


Fig. 1

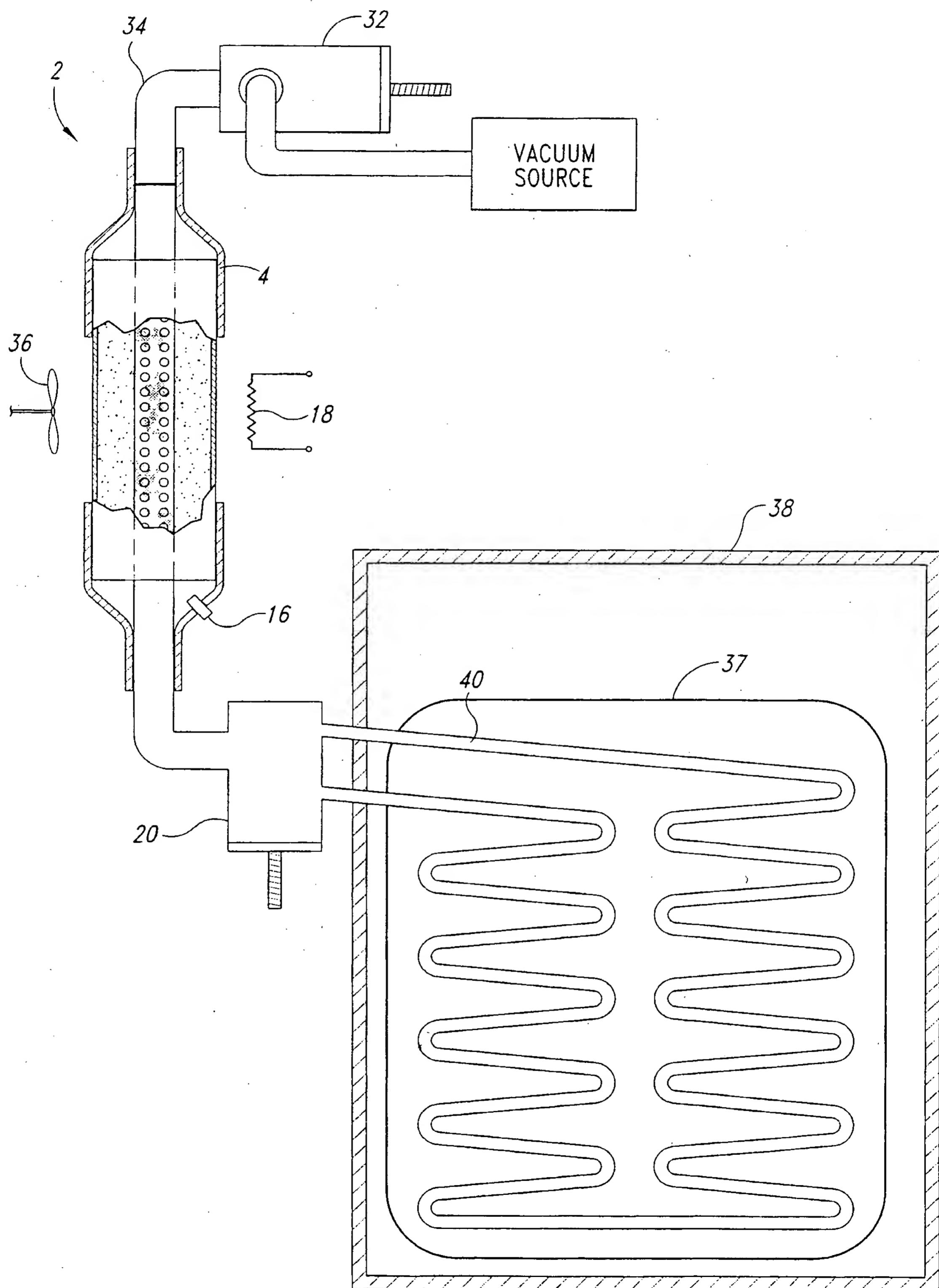


Fig. 2

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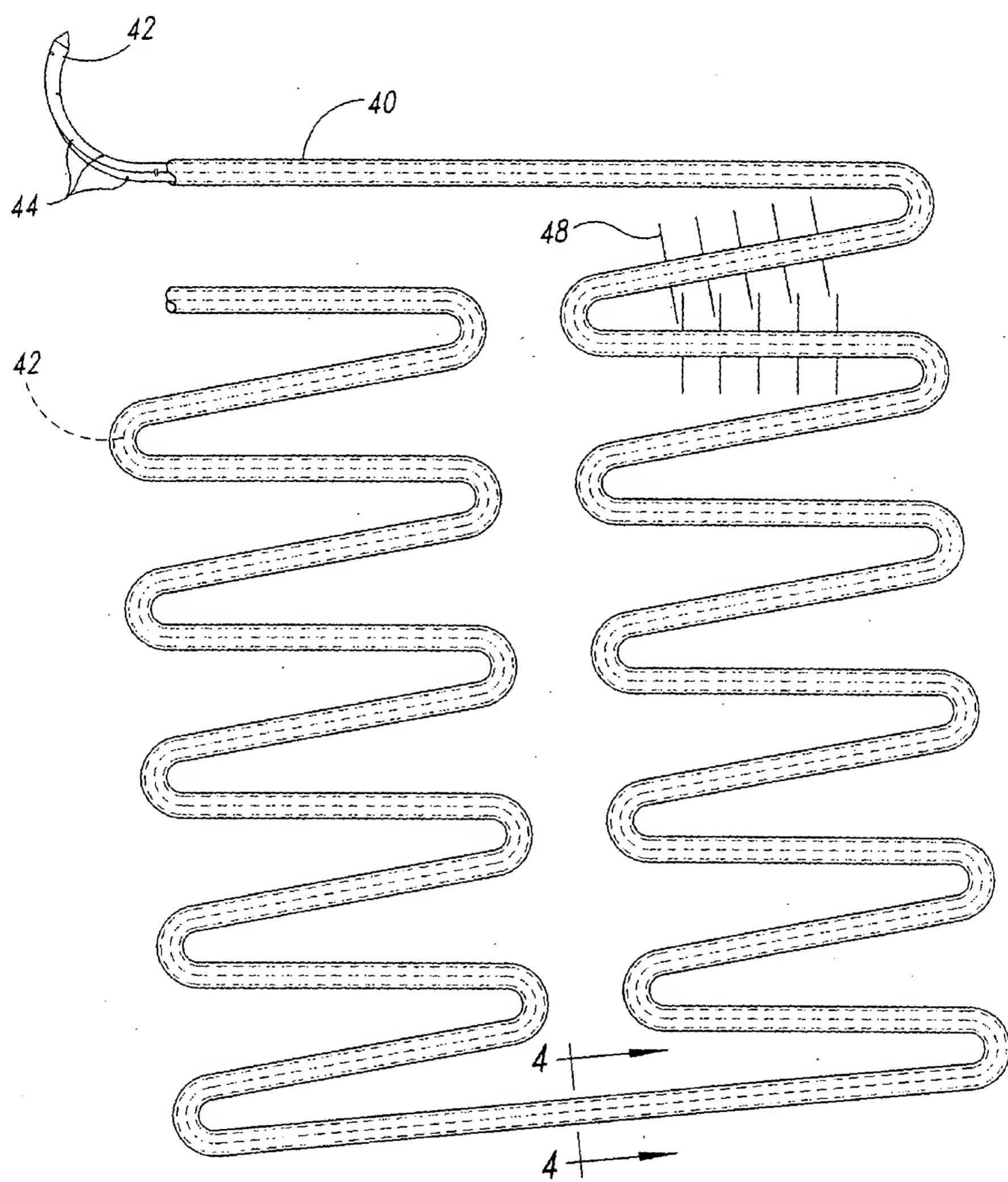


Fig. 3

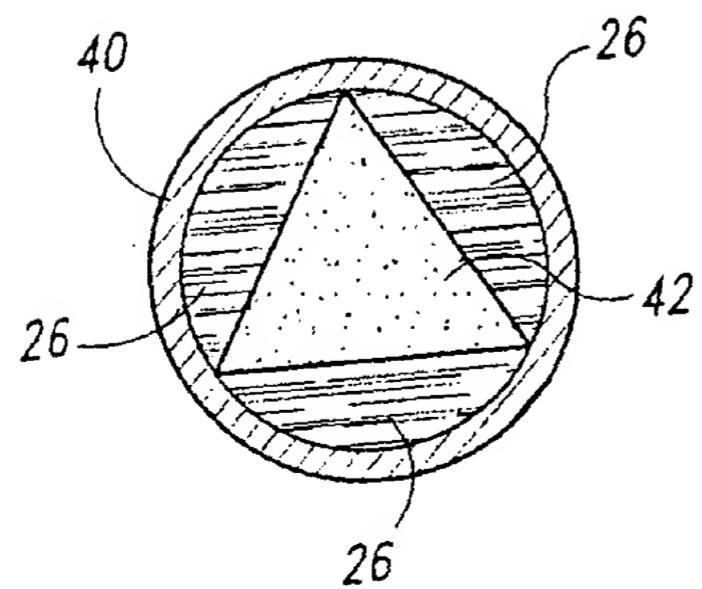


Fig. 4

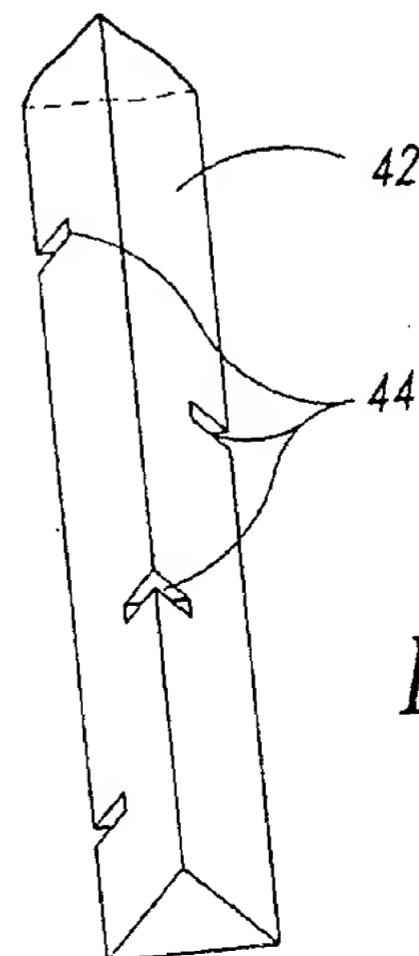


Fig. 5

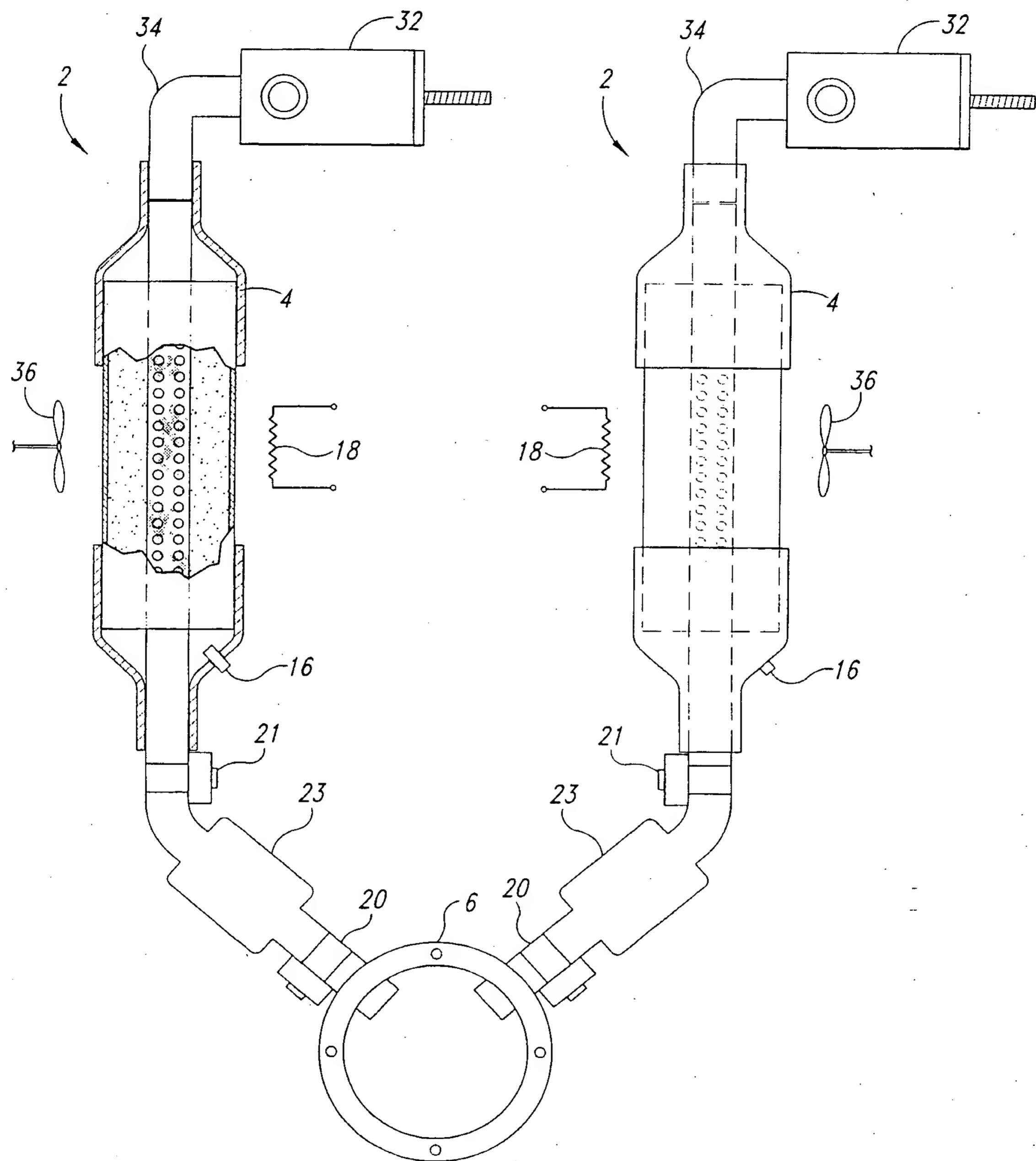


Fig. 6

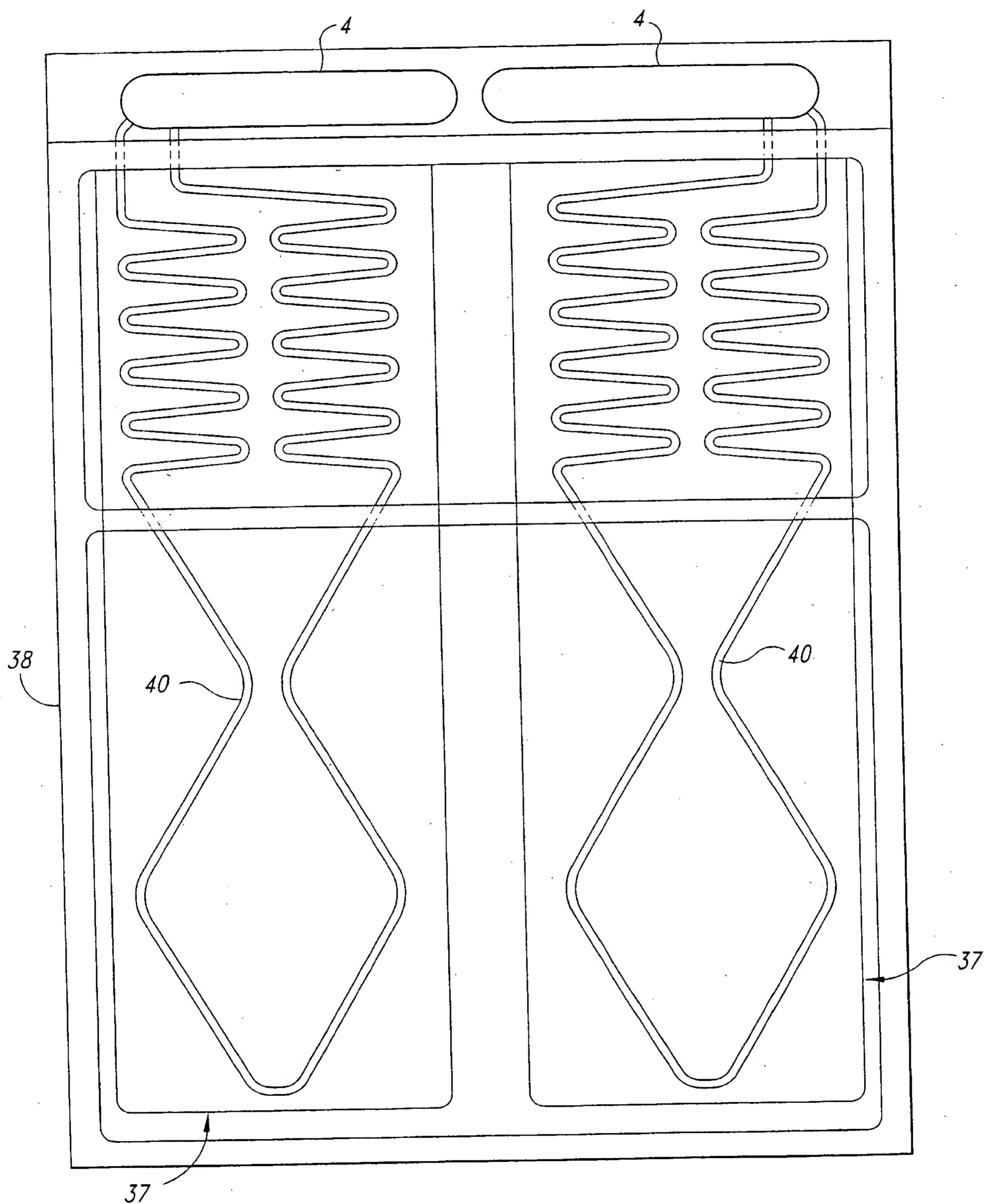


Fig. 7

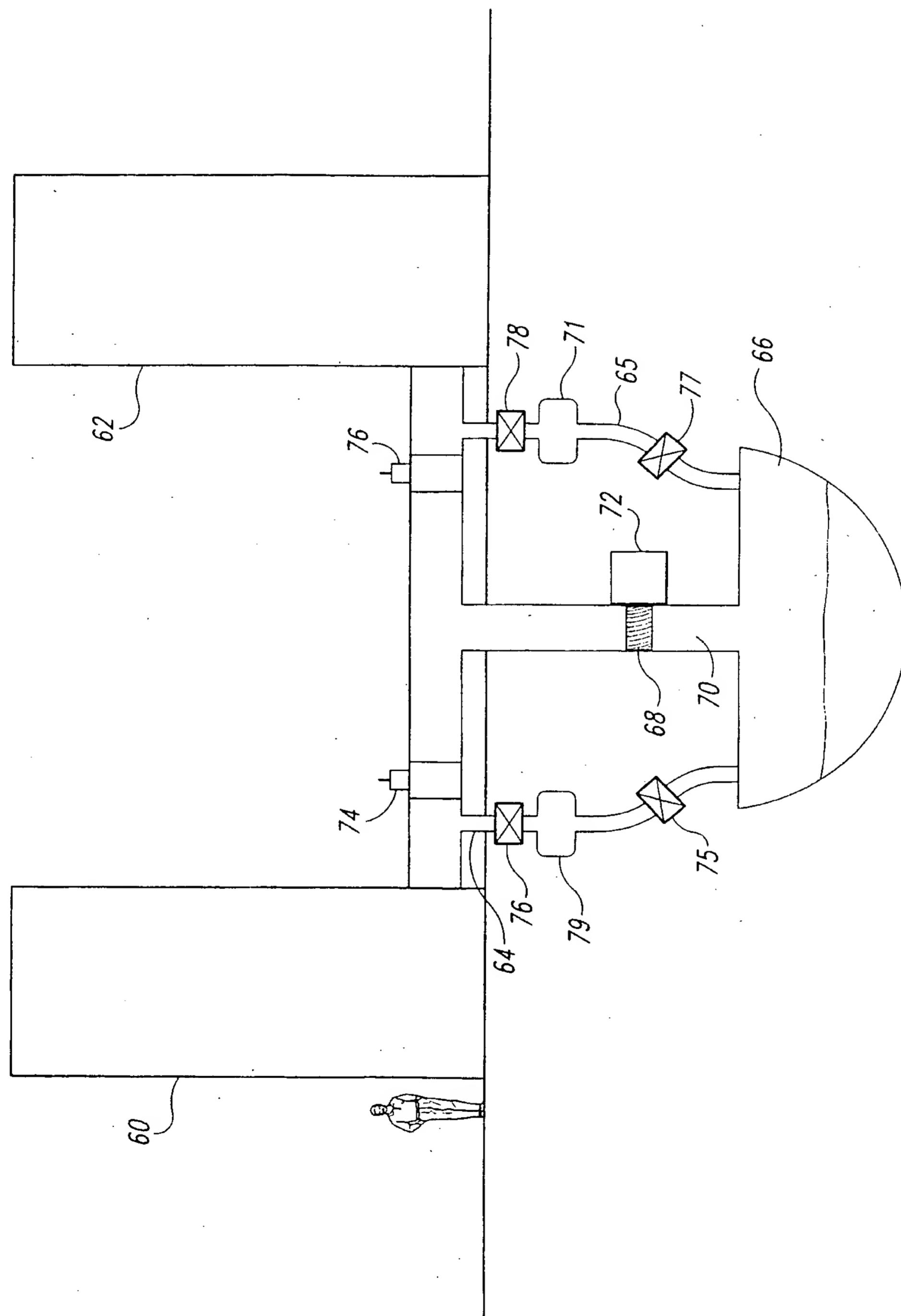


Fig. 8

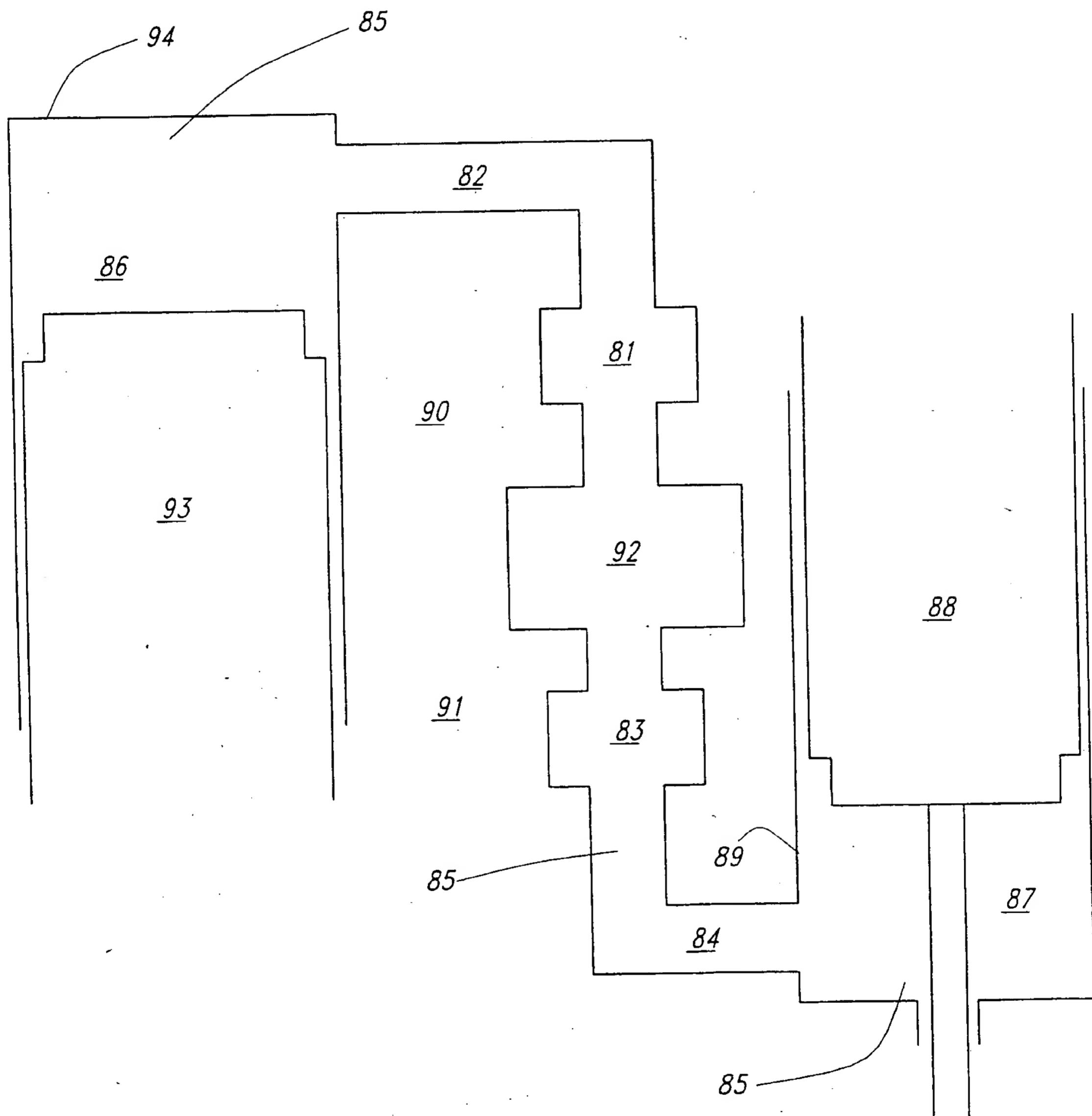


Fig. 9

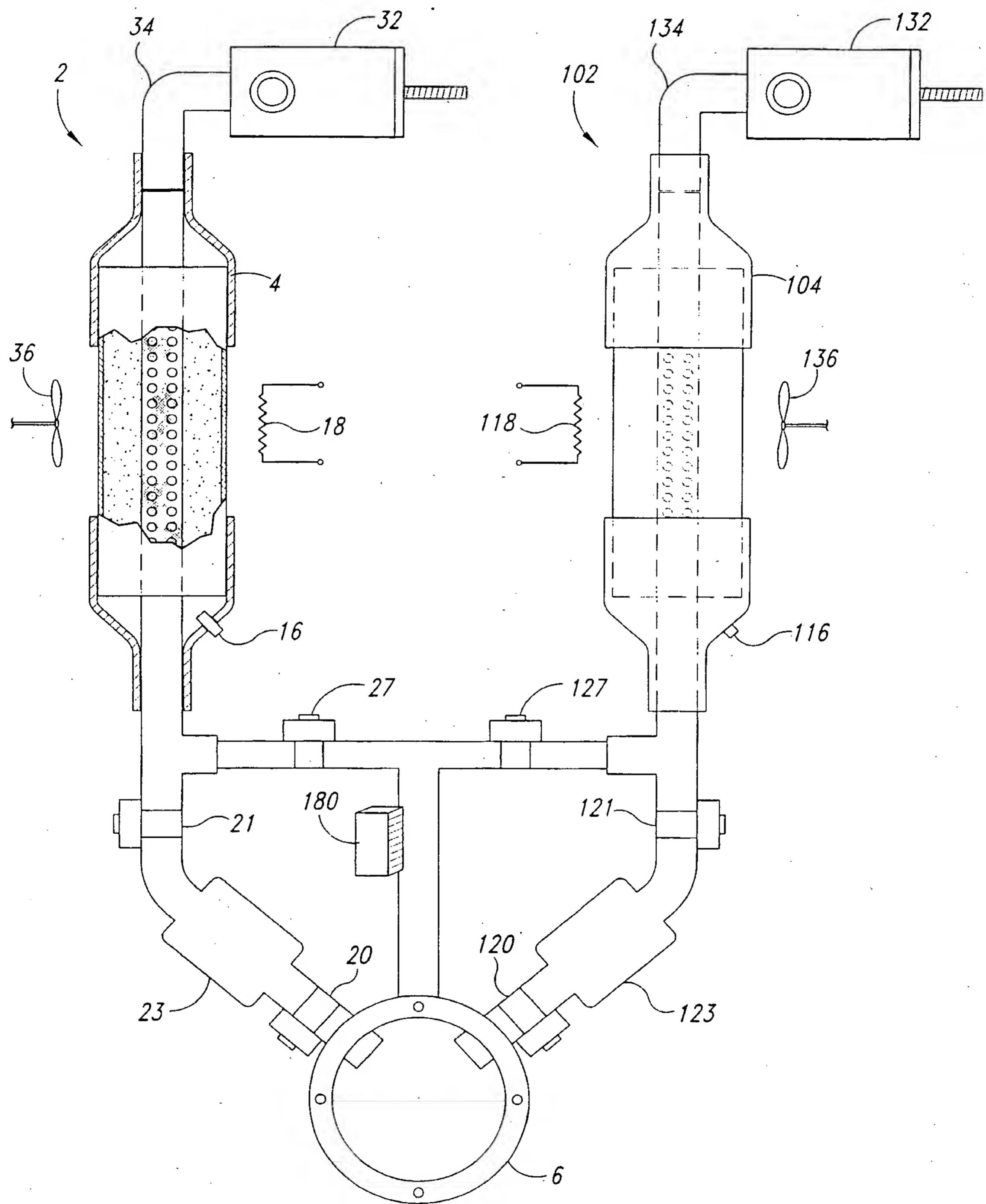


Fig. 10

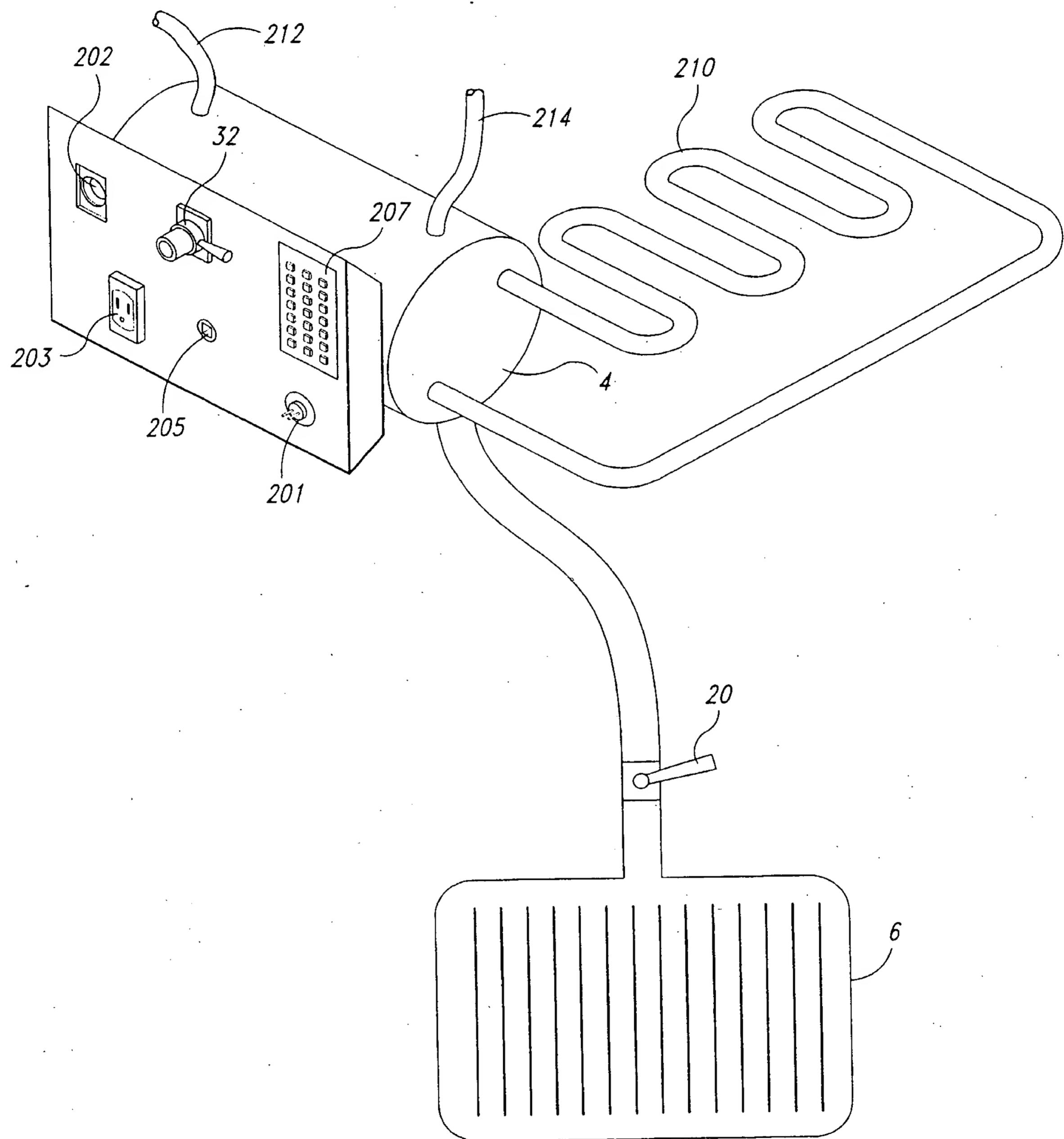
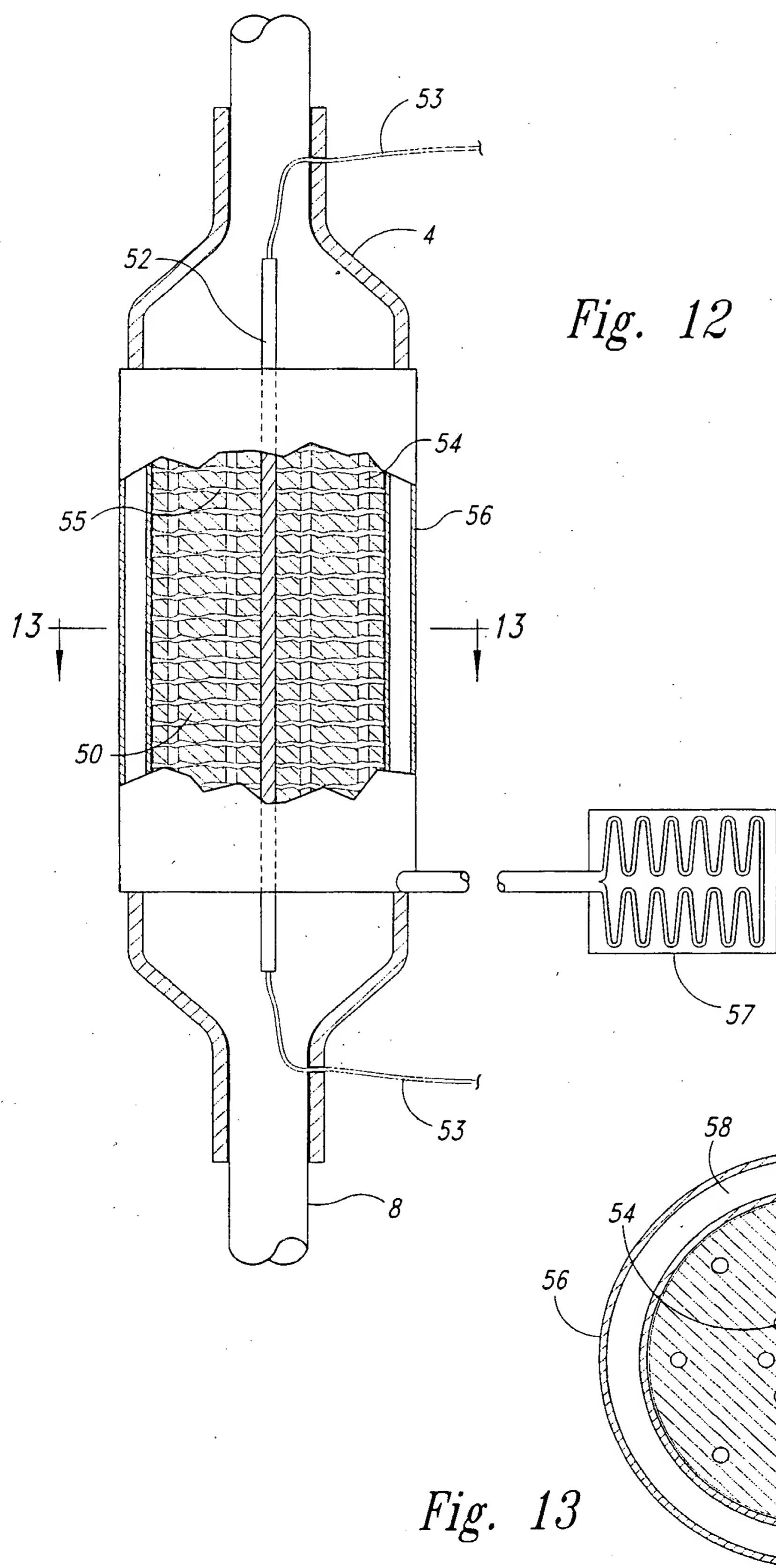


Fig. 11



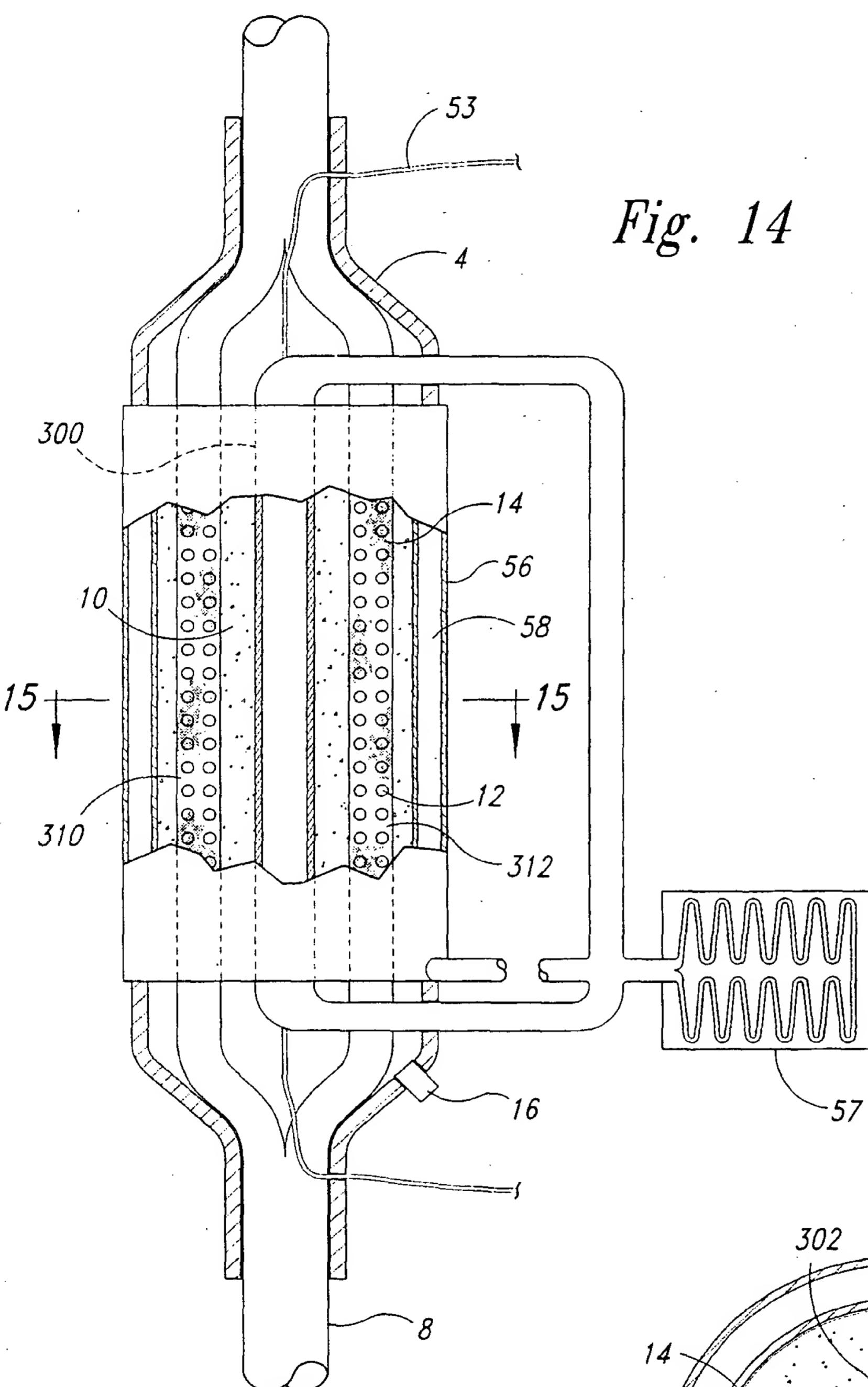


Fig. 14

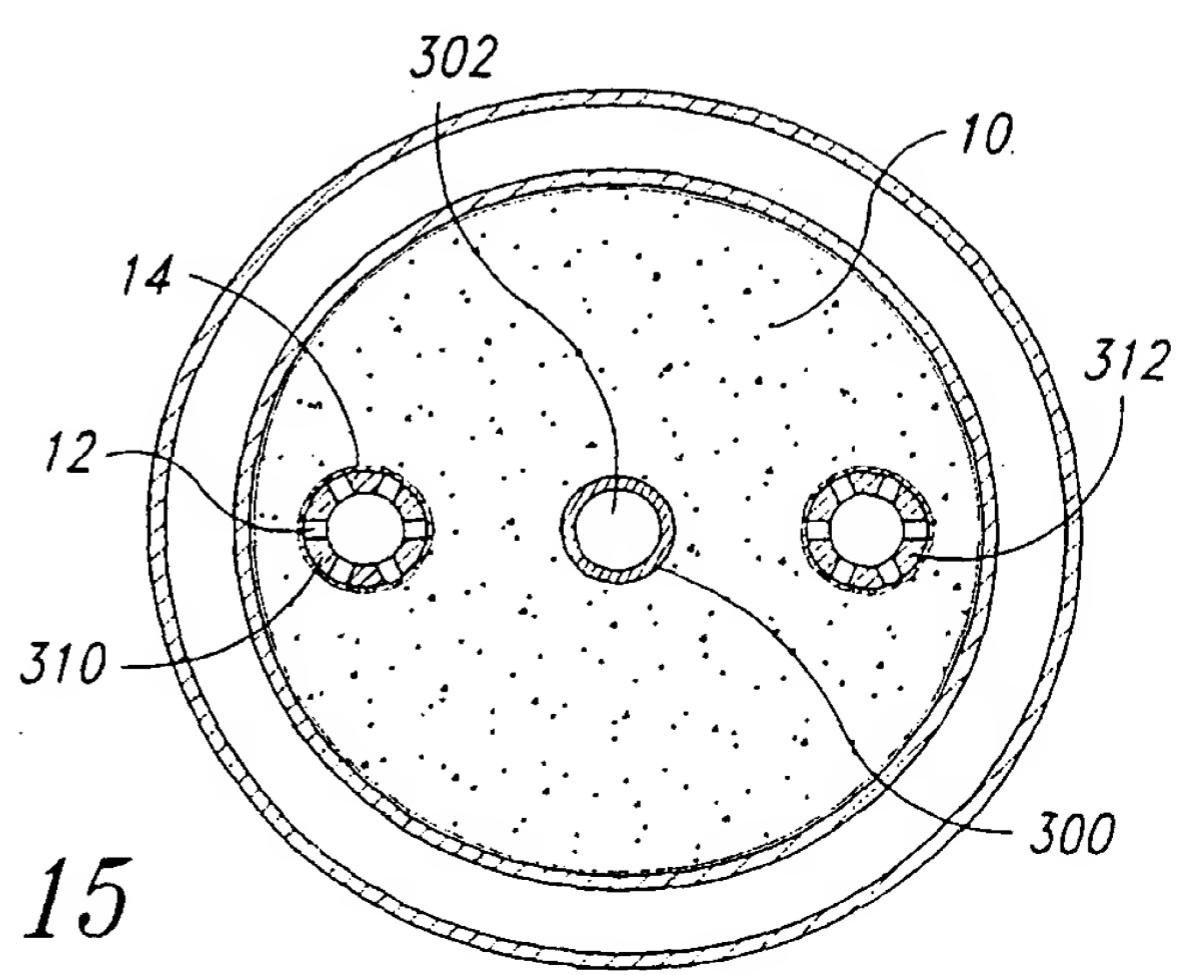


Fig. 15

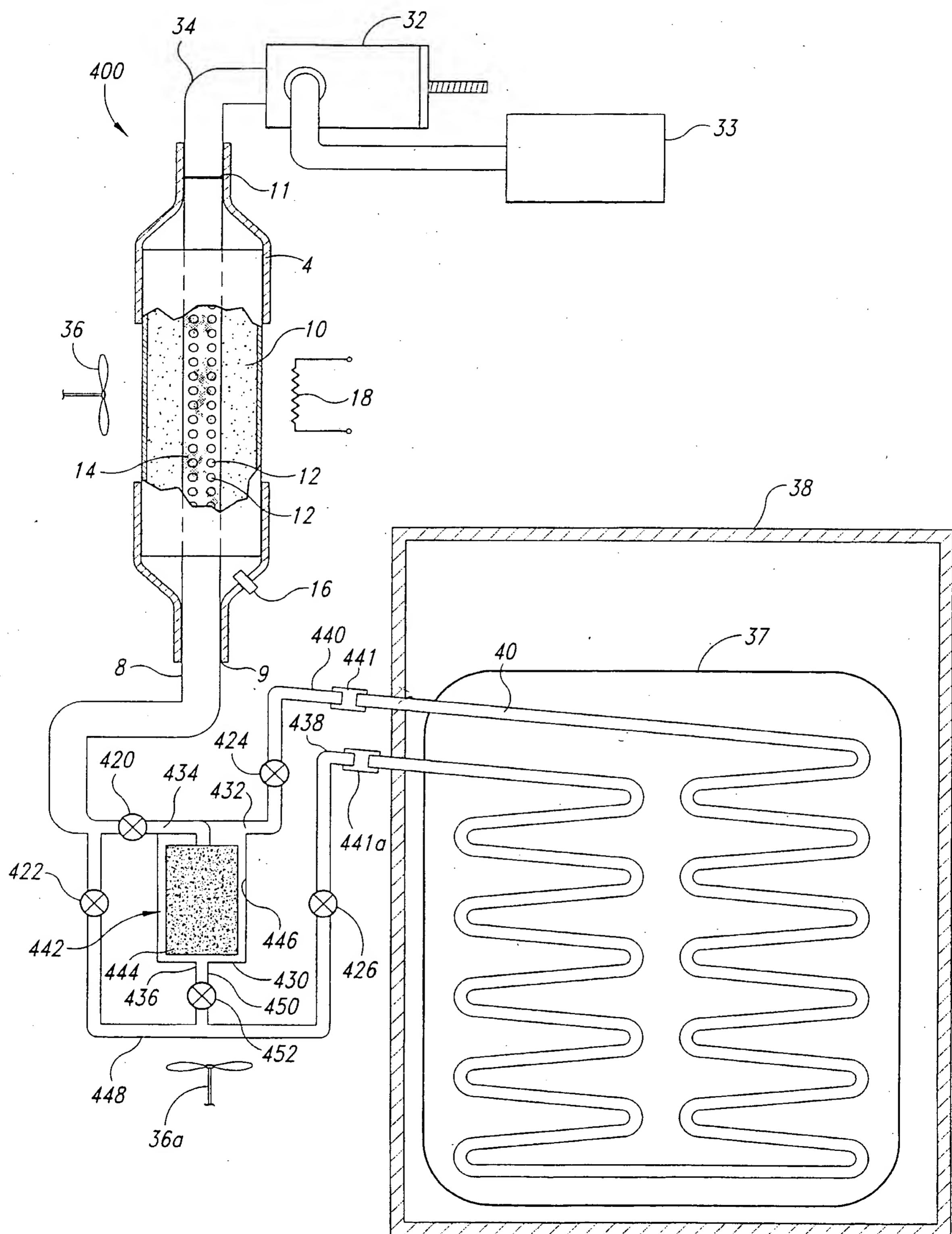


Fig. 16

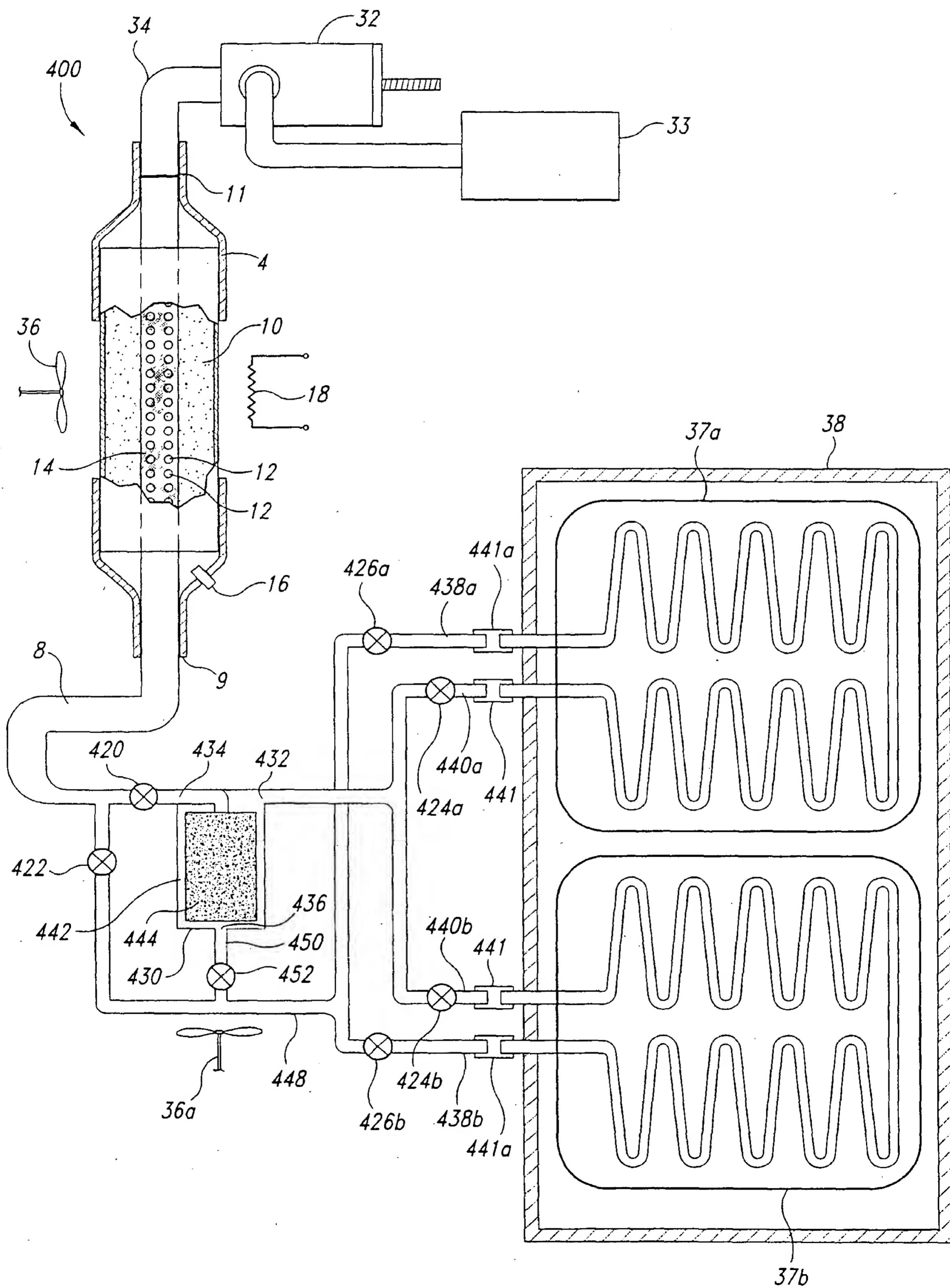


Fig. 17

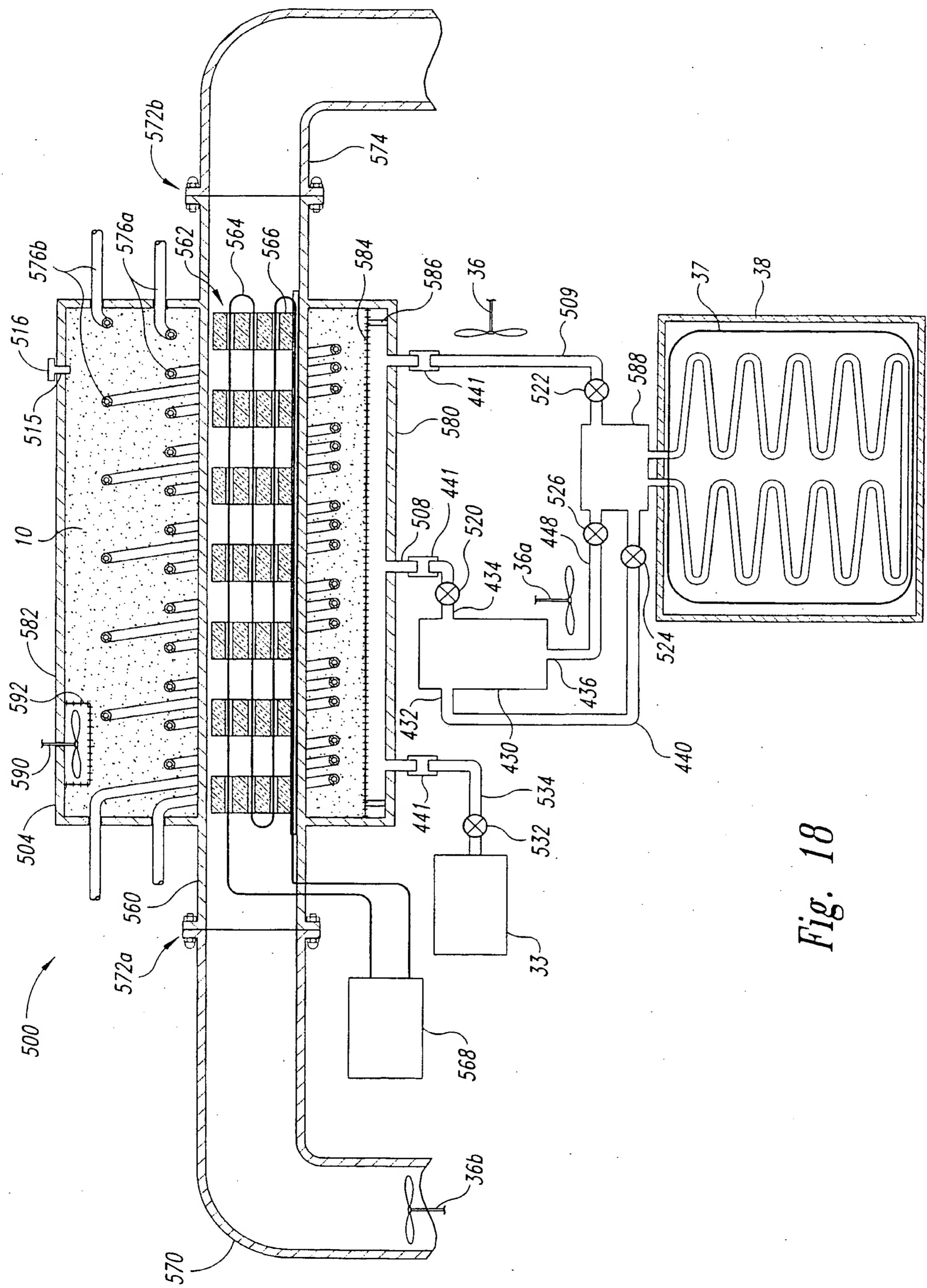


Fig. 18

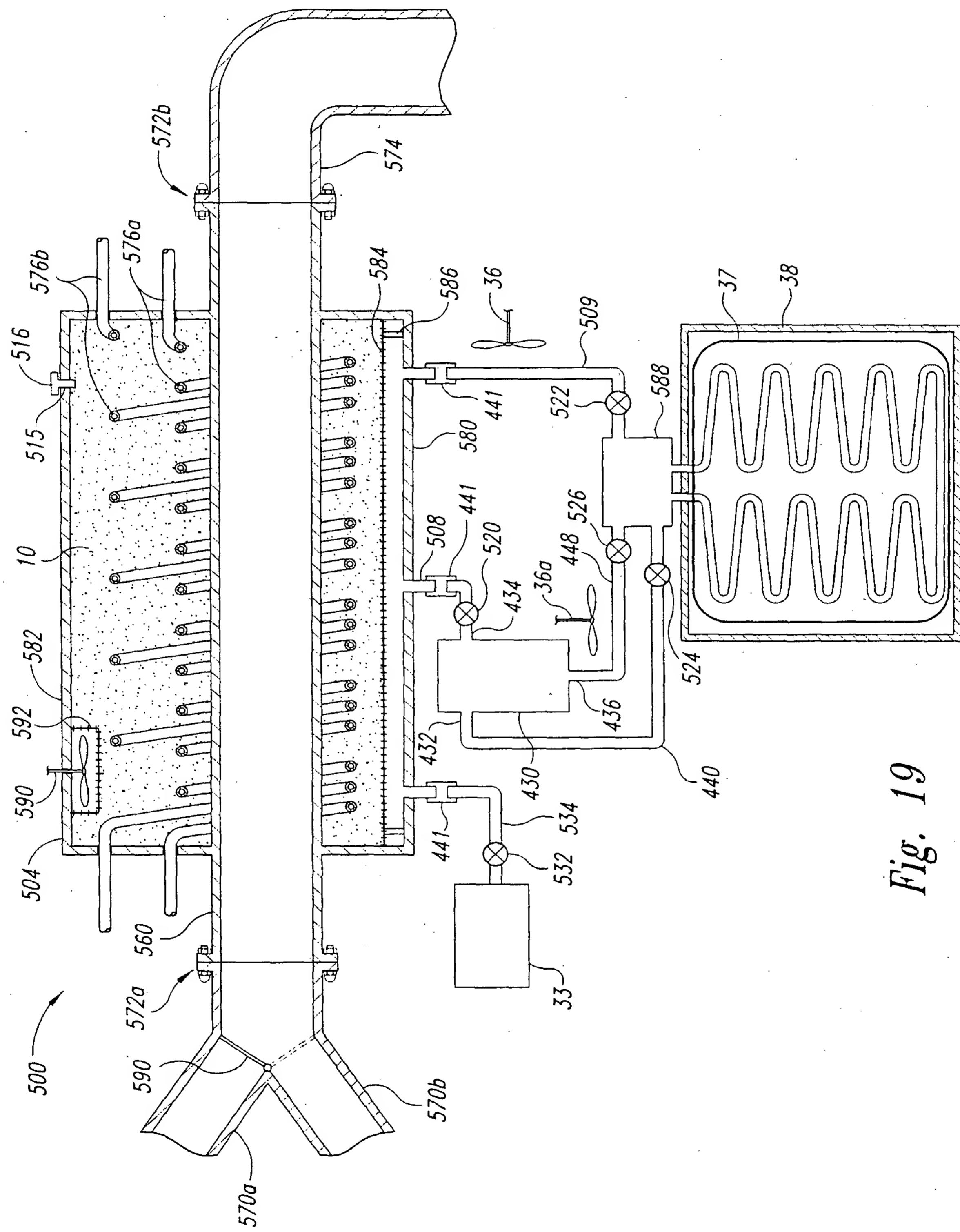


Fig. 19

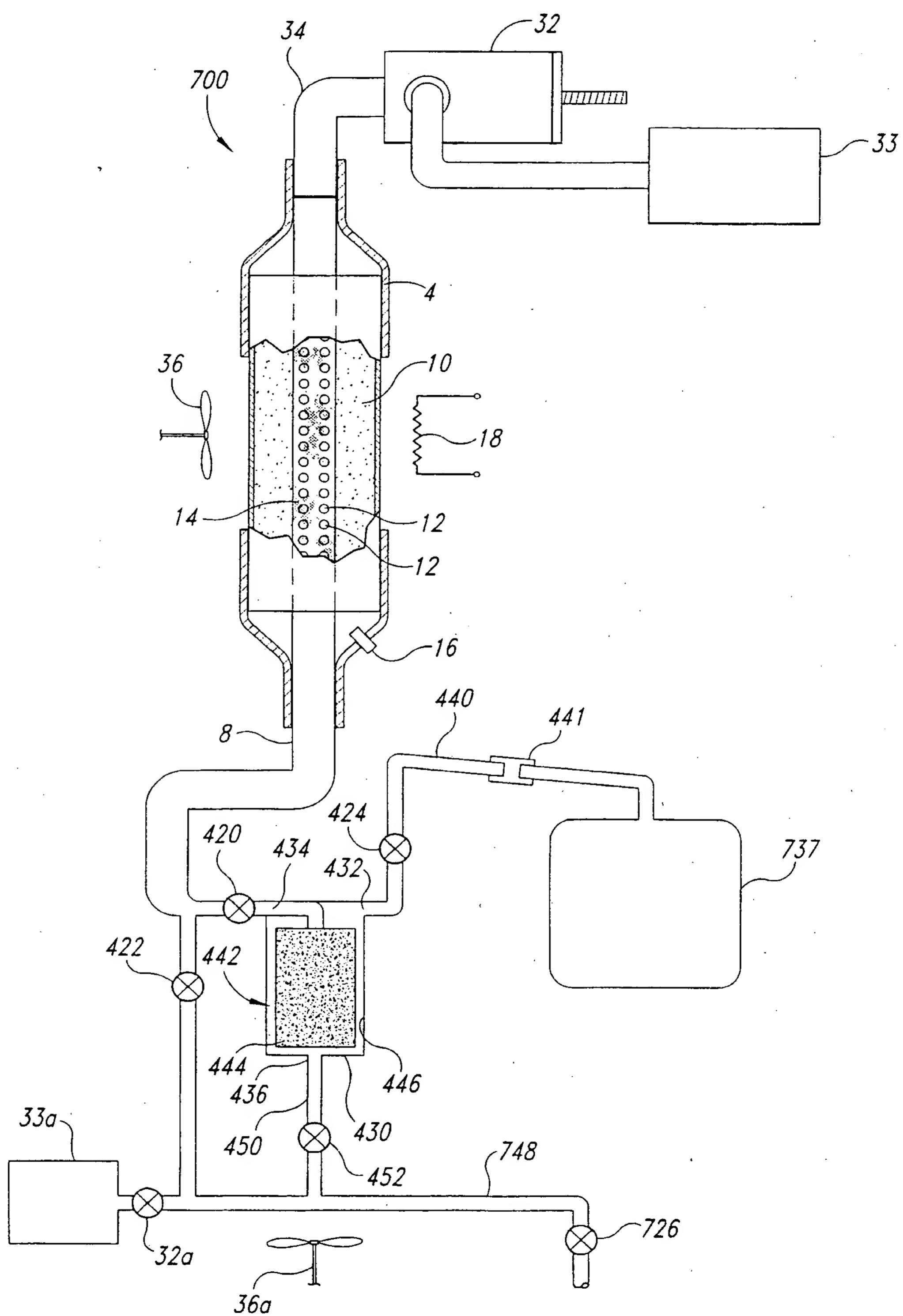


Fig. 20

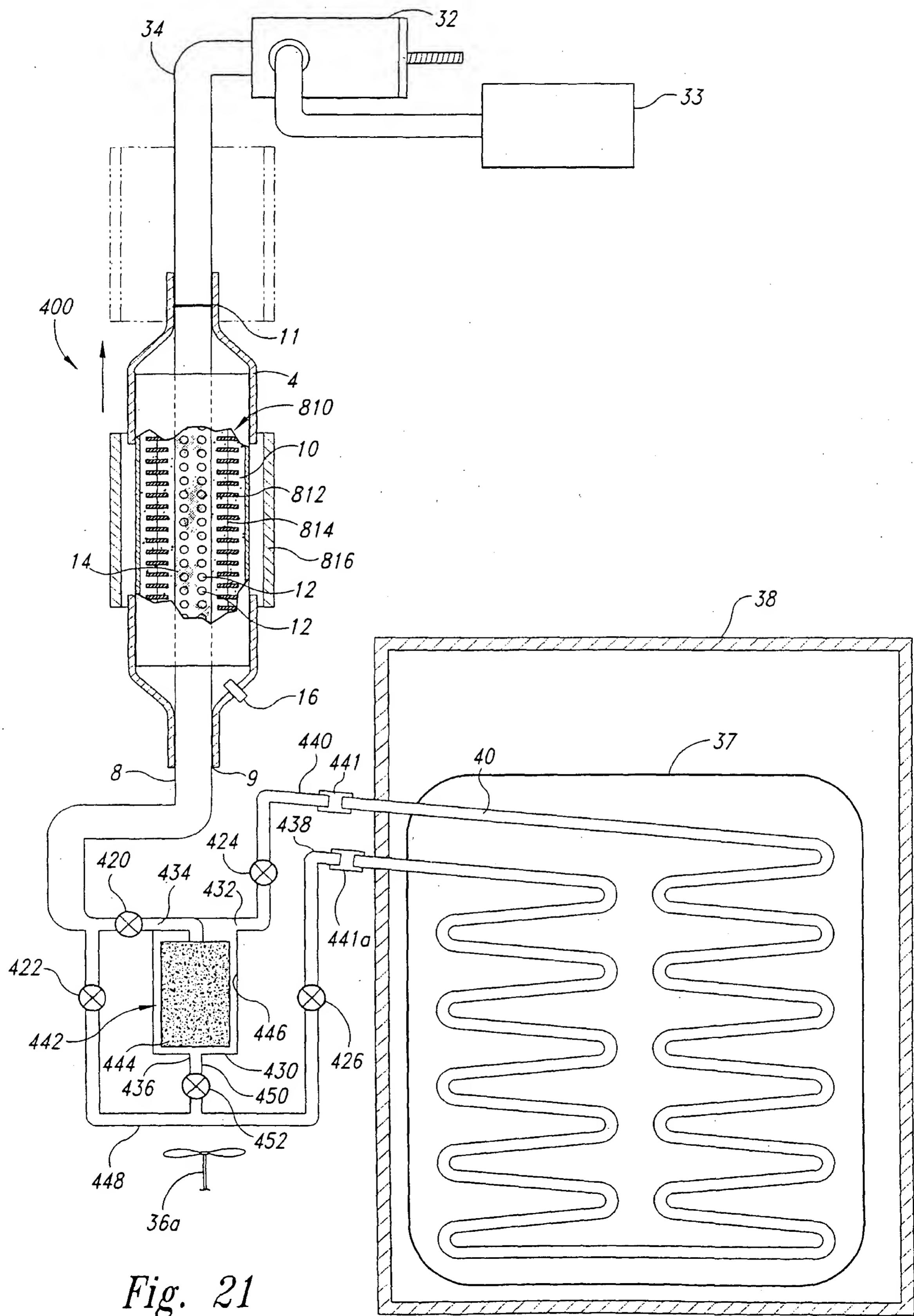


Fig. 21